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## Demonstration of a 532 nm Direct-Detection Imaging Laser Radar Using a Digicon Receiver

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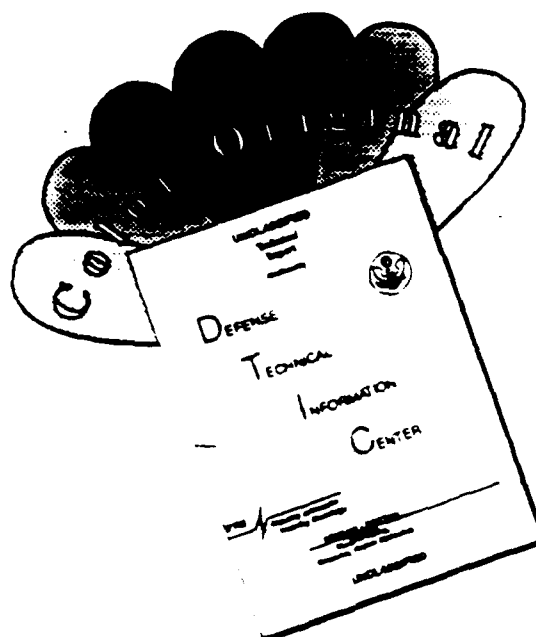
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13. ABSTRACT (Maximum 200 words)  A 532 nm direct-detection imaging laser radar using a prototype Digicon receiver was constructed and has demonstrated rapid multiple retargeting over a wide field of regard obtaining single-shot images with both intensity data and three-dimensional position data for each target. Such laser radar capability is important for discrimination and targeting. The Digicon receiver system obtains 8 × 8 - pixel images of multiple targets at a rate of 15 Hz. Each image provides both intensity and range-to-target at each pixel. Results of experiments involving seven targets located at various distances along a 60 m light tunnel are presented. Future directions discussed include acquisition and hand-off, tracking, long-range experiments (~1 km), and a 16 × 16 array Digicon tube with magnification.				
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## CONTENTS

1. INTRODUCTION .....	1
2. THE DIGICON RECEIVER .....	2
3. THE PROCESSOR .....	6
4. LASER RADAR EXPERIMENTAL SET-UP .....	9
5. EXPERIMENTAL PARAMETERS .....	12
6. RESULTS .....	13
7. FUTURE DIRECTIONS .....	21
8. SUMMARY .....	22
9. ACKNOWLEDGMENTS .....	22
REFERENCES .....	22
APPENDIX A - Computer-to-Laser Interface .....	25
APPENDIX B - DG Parallel Fix .....	27
APPENDIX C - Receiver Head Layout .....	29
APPENDIX D - Acquisition and Handoff Programs .....	31
APPENDIX E - Parameters for Outdoor Experiments .....	57
APPENDIX F - Laser Safety Analysis .....	59
APPENDIX G - Turn-on Procedures for the Digicon Experiment .....	77
APPENDIX H - Summary of Commands to Run the Digicon Laser Radar Demonstration .....	79

# DEMONSTRATION OF A 532 NM DIRECT-DETECTION IMAGING LASER RADAR USING A DIGICON RECEIVER

## 1. INTRODUCTION

Strategic defense systems have several requirements that lead toward the development of a long-range, short-wavelength laser radar. Among these requirements are discrimination between deployed warheads and decoys, acquisition of track files of threats, and targeting and aim-point selection. Key issues are precision three-dimensional target position measurement, agile access over an extended field of regard (FOR) and high resolution at each target. These long-range laser radar goals are being addressed with a 532 nm direct-imaging laser radar. Figure 1 illustrates the method of operation of this laser radar. This direct-detection laser radar provides both intensity and range-per-pixel information for each field of view (FOV).

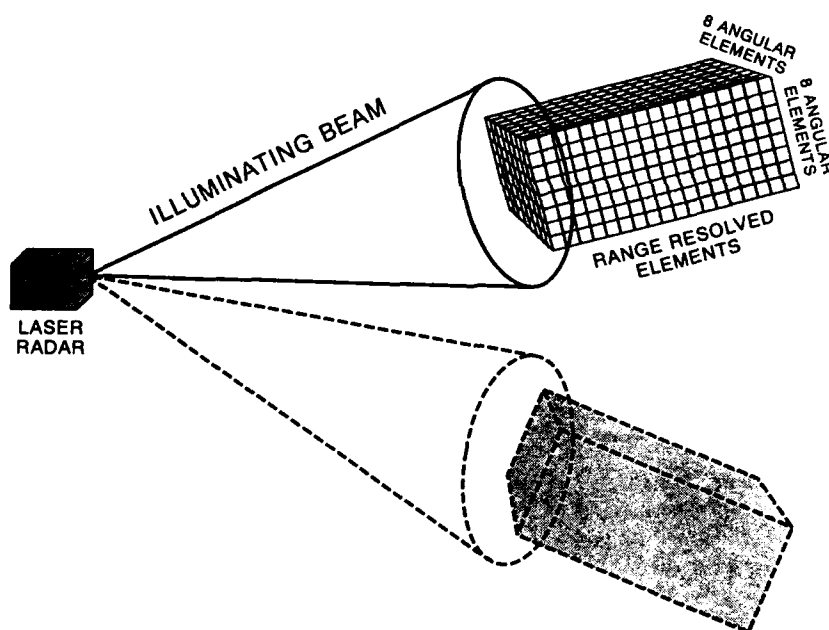


Fig. 1 — Concept for the direct-detection, short-wavelength imaging laser radar system for application against multiple targets

The short-wavelength imaging laser radar using a Digicon detector described here is desirable for several reasons. First, the short wavelength results in smaller optics for a space-borne system that achieves submeter resolution at megameter ranges. By comparison, a heterodyne laser radar [1] that uses a relatively long-wavelength CO<sub>2</sub> laser, does not have adequate angular resolution for imaging of long-range ballistic missiles or satellites. Second, the direct-detection imaging feature allows for detection of

multiple targets within a single FOV. Third, rapid retargeting of multiple targets distributed over a large FOR is achieved. Without the use of external steering optics, this capability is not present on most of the alternative systems such as the coherent laser-diode-based radar array [2] or the coherent ultraviolet pupil-plane detector array [3]. One competing technique, the rapid-optical beam-steering (ROBS) roving fovea telescope, has demonstrated 50 targets/second retargeting over a  $32^\circ$  FOR with  $3^\circ$  steps between targets [4]. This system incorporates a  $\text{CO}_2$  Doppler laser radar and a 0.5 m aperture beam director; no imaging is provided. More significantly, for space-based applications at  $10.6 \mu\text{m}$ , a 2 m aperture would be required to achieve comparable resolution; the 4 m mirror needed would therefore present both weight and pointing jitter problems. An electronically agile multiple aperture imaging scheme [5] which uses an image-reconstruction phase-retrieval algorithm has been proposed; for rapid retargeting, however, data processing times are always a concern. The closest alternative approach to providing the three-dimensional position and intensity information uses a streak camera with a fiber-optic converter [6]. For this system, however, external steering optics are still required. The Digicon laser radar receiver is therefore unique in that it is the only electronically agile direct-detection laser radar prototype receiver demonstrated to date.

The approach in this system incorporates a Digicon tube [7] as the focal plane detector. The Digicon provides a two-dimensional detector array of parallel analog signals that are processed to create both an array of amplitudes for a gray-scale image and an array of pulse arrival times for range information. The position control of the electron image in the Digicon tube allows rapid interrogation of any selected portion of a large photocathode, which coincides with the focal plane of a telescope, by an  $8 \times 8$  diode array. A gating mechanism is also incorporated into the Digicon tube to allow for high ambient background.

This short-wavelength laser radar experiment is configured with a Digicon receiver to detect nine targets positioned along a 60 m light tunnel. The system provides  $8 \times 8$  pixel range and intensity images for each target within a wide FOR.

This report proceeds as follows. Section 2 describes the Digicon receiver in this laser radar demonstration. Section 3 discusses the processor with a reference to Appendix A, the computer-to-laser interface. Section 4 describes the experimental set-up with references to Appendix B, the DG parallel fix, and Appendix C, the receiver head layout. Section 5 discusses experimental parameters. Section 6 presents the results. Section 7 describes future directions of interest with references to Appendix D, acquisition and handoff programs; Appendix E, parameters for outdoor experiments; and Appendix F, the laser safety analysis. Sections 8 and 9 are the summary and acknowledgments, respectively. Appendix G includes the turn-on procedures for the Digicon experiment. Appendix H is a summary of software commands to run the Digicon laser radar demonstration.

## 2. THE DIGICON RECEIVER

The receiver in this experimental system consists of a telescope and a Digicon tube arranged such that the photocathode of the Digicon tube sits in the focal plane of the telescope. In this demonstration, the telescope is a standard photographic 350 mm Hasselblad lens. The basic Digicon detector is similar to that used in the NASA Hubble Space Telescope and is illustrated in Fig. 2 [7]. Light impinging on the photocathode at one end of the tube stimulates the emission of electrons. These photoelectrons are then linearly accelerated through the tube by a series of copper annular accelerator rings separated by ceramic insulating cylinders and eventually collected by a small diode array at the anode. The linear acceleration is achieved by connecting the 15 accelerator rings to a high-voltage power supply ( $\sim 20 \text{ kV}$ ) through a resistive divider network. Focussing of the electron image at the anode is established by an axial magnetic field. Deflection coils provide a controlled transverse magnetic field so that electrons from any selected portion of a large 30 mm photocathode can be deflected to the small diode array. The

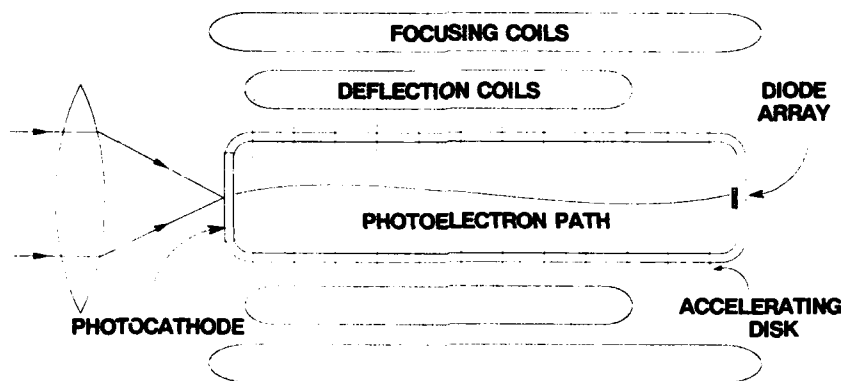


Fig. 2 — Digicon receiver comprises optics, a magnetically focused Digicon tube with electron image deflection, and a diode array with parallel signal output

photoelectrons are detected by the  $8 \times 8$  silicon diode array via electron bombardment in silicon yielding approximately 5000 electron-hole pairs for a single 20 keV photoelectron. The Digicon tube body is approximately 15 cm long and 6 cm in diameter.

Figure 3 illustrates the  $8 \times 8$  silicon diode array. The diode array was fabricated from high-resistivity n-type silicon. An  $8 \times 8$  array of p+ pixel regions on 100 micron centers was diffused into the back surface, and a thin n+ region on the front surface provides a uniform bias. Signal output pads were deposited at each pixel for gold-on-gold bump-bonding to a fan-out structure of gold on a sapphire substrate. Scans of the optical response of the resulting diode array show no dead zones between adjacent pixels [7].

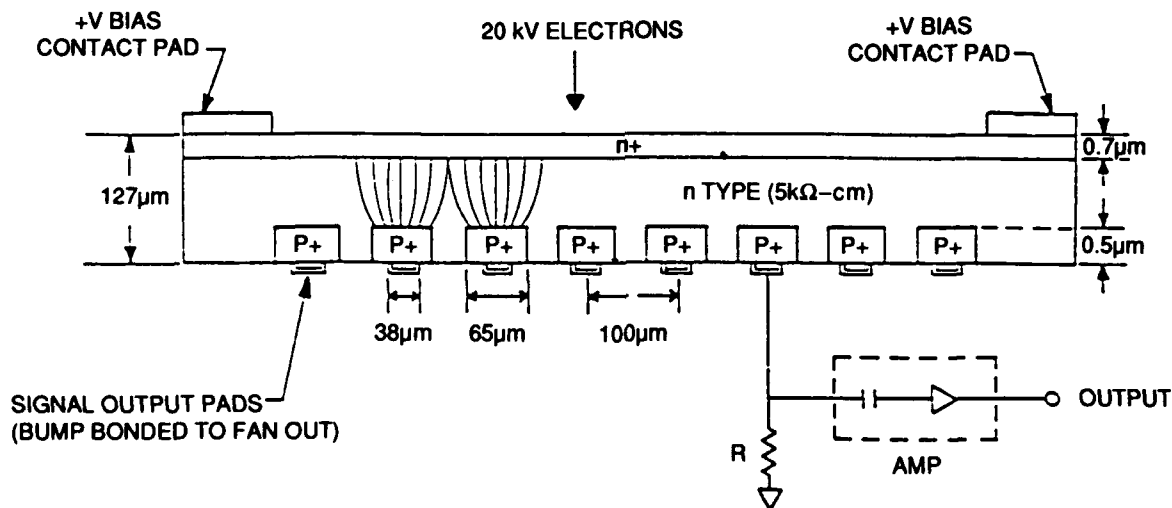


Fig. 3 — Cross-sectional drawing of the  $8 \times 8$  diode array used in the prototype Digicon detector

The sensitivity and time resolution of the Digicon with an  $8 \times 8$  diode array have been measured using a nitrogen laser with a 0.5 ns pulse output. Figure 4 shows the electronic signal through a 200 MHz filter, preamplifier, and amplifier. Through a calibration procedure, the diode response to the laser pulse was determined to be equivalent to about 28 photoelectrons. The noise typical of this particular electronic configuration is equivalent to about 1 photoelectron RMS which is also shown in the figure.

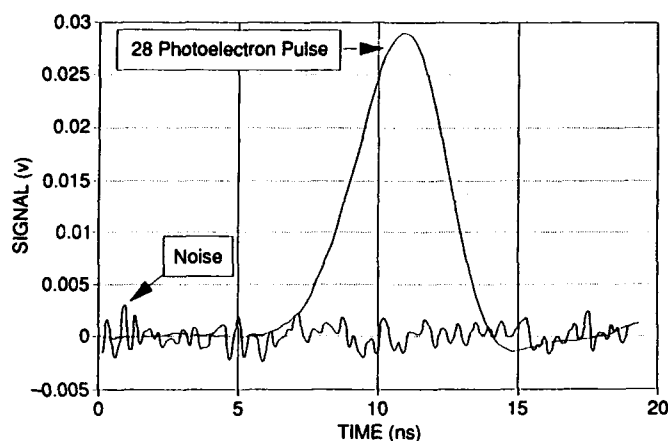


Fig. 4 — Pulse response of the Digicon with  $8 \times 8$  diode array using a 200 MHz filter and also showing electronic noise with zero signal

The jitter in the detection of the arrival time of an optical pulse at the Digicon was measured using five separate electronic configurations. The time jitter data, illustrated in Fig. 5, indicates the time resolution achievable with the Digicon and the associated electronics. The abscissa gives the signal threshold that is necessary to achieve a 100-Hz false alarm rate (FAR); the time jitter of the ordinate is obtained with a detection probability of 0.9. The lowest time jitter was obtained using a direct analog amplifier and a 200 MHz filter in the same configuration as used for the data in Fig. 4. The other four experimental values were obtained using charge-integrating preamplifiers followed by a pulse-shaping amplifier in various configurations. Clearly, the charge integrating techniques can be used to improve sensitivity to the point of single photoelectron detection at the expense of reduced time resolution sensitivity. The smooth curve is a fit to an inverse square root of the frequency, which is typical of electronic noise vs bandwidth. The different configurations have different shaped pulses and corresponding pulse lengths; these lengths are also illustrated in Fig. 5. This feature is important because the detector cannot be used to measure the pulse arrival time and range of a second target following a first target until the pulse-length time has elapsed to allow a recovery of the baseline for the threshold detection. The data in Fig. 5 indicate an operating point for the Digicon using a charge-integrating amplifier with a time resolution of about 2 ns, a signal detection threshold of 1.8 photoelectrons, and a detector reset time of less than 100 ns. Table 1 summarizes the high-speed Digicon performance for this demonstration.

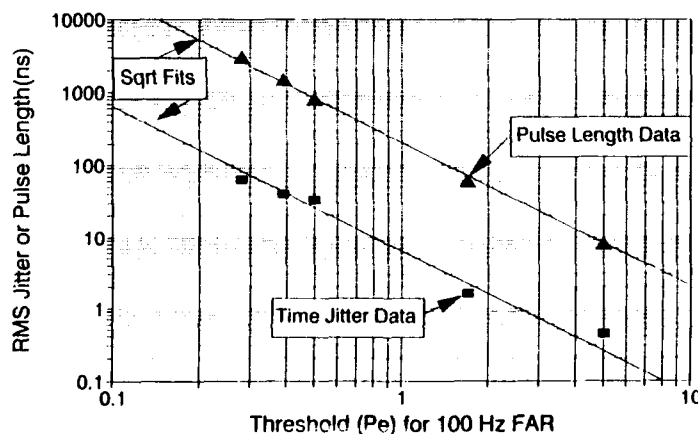


Fig. 5 — RMS timing jitter and pulse length vs threshold for the Digicon with  $8 \times 8$  diode array



Table 1 — High-speed Digicon Performance

Analog Signal Bandwidth	200 MHz
Analog Noise Equivalent	1 Photoelectron RMS
Detection Threshold (100 Hz False Alarm Rate)	10 Photoelectrons
90% Detection Probability Average Signal	15 Photoelectrons
Maximum Linear Signal	3000 Photoelectrons
Time Resolution	< 1 ns RMS

An S-20 photocathode was selected to allow for versatility in transmitter sources, as Strategic Defense Initiative requirements were subject to change, and to minimize development risk. Figure 6 shows the relative spectral response curve. The measured photocathode quantum efficiency at 532 nm was 3.5%. Recently available GaAs photocathodes have demonstrated up to 40% quantum efficiency at 532 nm, but it was not the intention here to stress sensitivity with this initial prototype device. During initial testing of the receiver, ultraviolet response at 308 nm with a XeCl excimer laser was also confirmed.

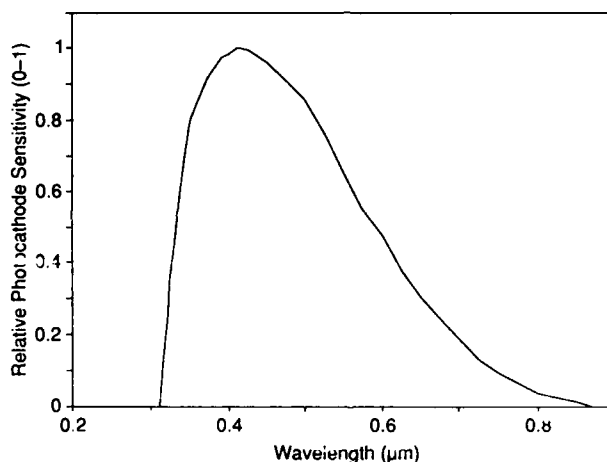


Fig. 6 — S-20 photocathode response as a function of wavelength

Several techniques are used to protect the Digicon from high photocathode currents. A 532 nm narrowband filter is mounted just before the photocathode. A 3 OD (optical density) neutral density filter is positioned just in front of the telescope lens. Most significantly, the Digicon tube is gated on only for the laser pulse return. This aperture gating is established by tying the photocathode to the same potential as the second accelerator ring away from the photocathode while leaving the intermediate accelerator ring at a fixed potential. The reversal thereby created in the field potential gradient quenches the emission of photoelectrons and gates the tube off [8]. The Digicon tube gating is coordinated with the laser trigger, and the tube is gated on for 5  $\mu$ s to account for laser firing jitter and to cover a variation in range-to-target of up to 1 km.

The telescope in front of the Digicon tube was selected to give the angular FOR and FOV required for a given experiment. The angular FOR and FOV are given by

$$\text{FOR} = \tan^{-1} \left[ \frac{D_C}{f} \right] \quad (1a)$$

$$\text{FOV} = \tan^{-1} \left[ \frac{D_A}{f} \right] \quad (1b)$$

where  $D_C$  is the diameter of the photocathode (i.e., 30 mm),  $D_A$  is the size of the diode array (i.e., 0.8 mm), and  $f$  is the focal length of the telescope. In this demonstration, a 350 mm telescope lens yielded a  $4.9^\circ$  angular FOR. (An 80 mm lens yielding a  $22.6^\circ$  FOR was also used.) Figures 7(a) and (b) depict the photocathode footprint and the  $8 \times 8$  diode array footprint, respectively, as a function of range for various lens focal lengths. With the 350 mm lens, the diode array footprint varies from 5.7 cm at a range of 25 m to 13.7 cm at 60 m; these were convenient dimensions for constructing targets that were of shapes recognizable with an  $8 \times 8$  pixel image and that could be easily rotated.

In this laboratory demonstration, the detector FOV is much larger than the receiver's diffraction-limit; therefore, speckle fluctuations do not affect the system. In a realistic scenario of megameter ranges, however, diffraction-limited optics would be used, and speckle becomes an issue as it would in any radar system that uses a coherent laser as a transmitter. The typical solution would be temporal averaging over several pulses.

### 3. THE PROCESSOR

Figure 8 shows the processor components that support the Digicon receiver. The analog signal from each of the 64 amplifiers is split into timing and intensity signals. Sixty-four time-to-digital converters record the arrival time of the signal on each element of the  $8 \times 8$  array relative to the laser trigger pulse. The intensity signals are digitized by 64 integrating analog-to-digital converters to record the intensity on each element. After each laser pulse, the digital data are transferred to an 80286 computer (IBM PC AT) which analyzes, stores, and displays the data. The three-dimensional target location is displayed in real time via various intensity and time (range) displays. A graphics monitor presents real-time pseudocolor range-per-pixel and intensity-per-pixel images for each laser pulse. In addition to processing the return signals, the computer controls

- the trigger for the Digicon gating circuit and the laser firing,
- the laser pointing via the beam director, and
- the current through the Digicon deflection coils to steer the FOV of the  $8 \times 8$  array around the FOR.

Appendix A describes the computer-to-laser interface that enables control of the laser firing from the computer. Figure 9 shows the processing electronics, the graphics monitor, and the Sun workstation.

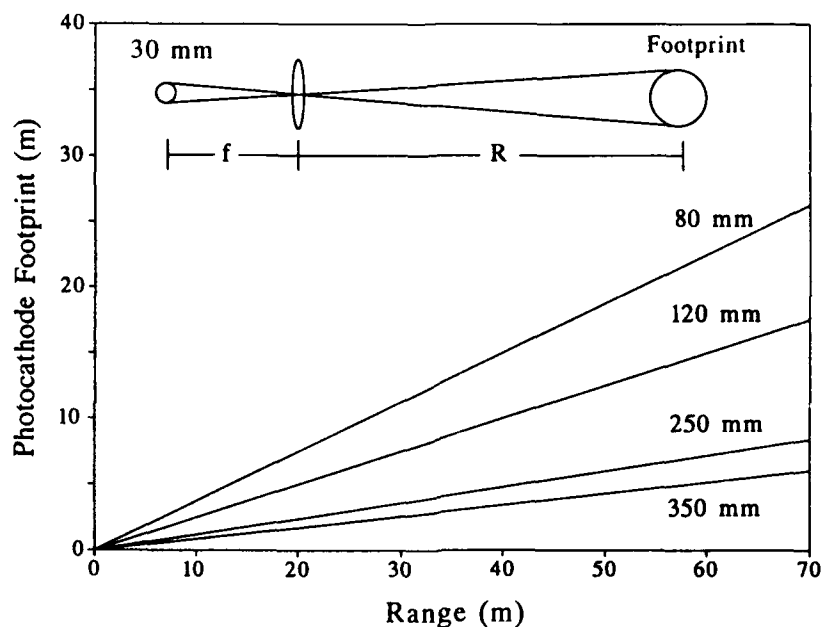


Fig. 7(a) — Digicon photocathode footprint vs range for lenses with different focal lengths  $f$

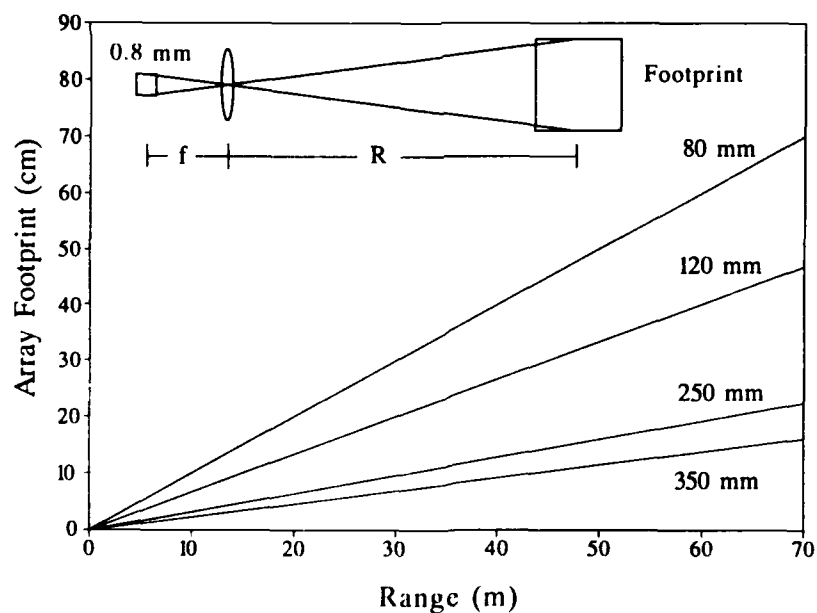


Fig. 7(b) — Digicon diode array footprint vs range for lenses with different focal lengths  $f$

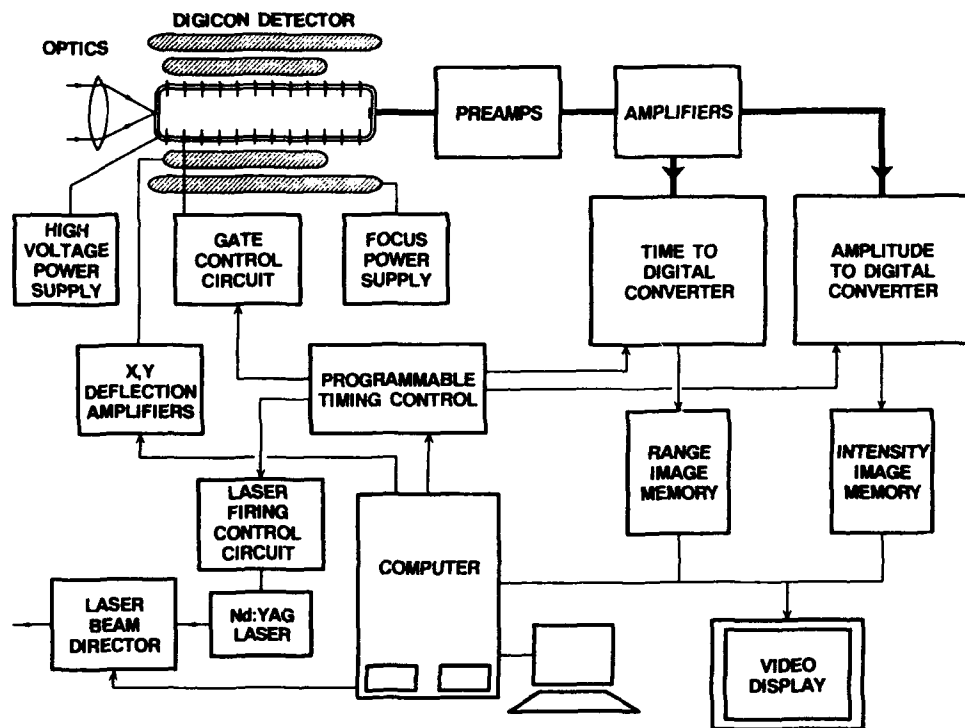


Fig. 8 — Schematic of the Digicon receiver and processing electronics for the NRL demonstration



Fig. 9 — Processing electronics with display monitor and a Sun workstation

#### 4. LASER RADAR EXPERIMENTAL SET-UP

Figure 10 illustrates the short-wavelength laser radar experimental set-up. The Digicon Receiver Head is connected via 64 cables (for the  $8 \times 8$  diode array) to the processing electronics which includes the 80286 computer. At present, the microcomputer uses established target lists to control the Digicon deflection and the beam director. A video camera connected to a frame grabber in a Sun 4/370 workstation provides a means of developing an acquisition and handoff capability. After locating a target in the video camera's FOV, the workstation will pass the target coordinates to the microcomputer for pointing the Digicon's FOV and the laser beam. (The lenses chosen for the video camera and the Digicon tube were selected to approximately match the camera's FOV with the Digicon's FOR.) Table 2 summarizes key experimental parameters.

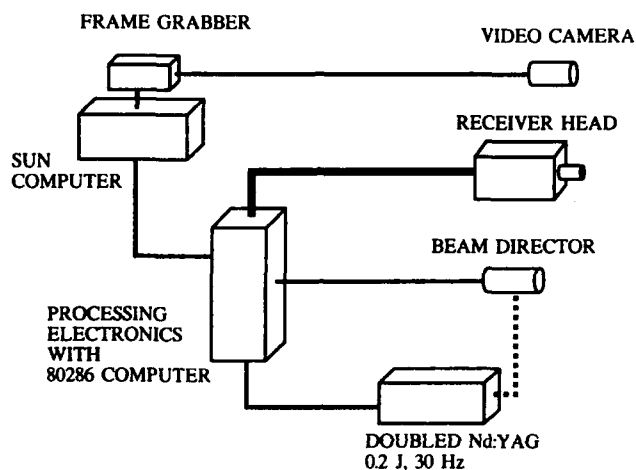


Fig. 10 — Block diagram of the short-wavelength laser radar experiment

Table 2 — Experimental Parameters for the Digicon Receiver Demonstration

Laser Beam Energy (at Beam Director)	87 mJ
Laser Beam Diameter (at Beam Director)	7 mm
Laser Pulse Width	10 ns
Illumination Uniformity	< 20%
Laser Filter	
Center Wavelength	532.1 nm
Spectral Width	3.4 nm
Detector Responsivity Uniformity	< 10%
Digicon Receiver FOV	
80 mm Telescope	10 mrad
350 mm Telescope	2.29 mrad
Digicon Receiver FOR	
80 mm Telescope	394 mrad
350 mm Telescope	86 mrad

The transmitter in this experiment is a doubled, Q-switched, Nd:YAG Continuum laser (Model 661). Operating at 30 Hz, it delivers 200 mJ/pulse with 10 ns pulse duration. The laser beam is sequentially pointed at individual targets by mechanical beam-steering mirrors (General Scanning Model XY-3037 scan head with DG-1003 controller) of 2.54 cm clear aperture; these mirrors can be rapidly retargeted over  $\pm 22^\circ$ . The scanner retargeting time is  $0.3^\circ/\text{ms} \pm 5\%$ . In this experiment with a scan coverage of  $3^\circ$ , retargeting and settling time consumes 11 ms; therefore, the scanner can handle speeds up to 90 Hz. Appendix B describes the "DG-Parallel Fix" required to successfully communicate between the computer's parallel printer port and the parallel input port on the beam director.

Figure 11 shows the Digicon receiver and laser beam director. The Digicon tube and deflection coils along with a high-voltage power supply, 64 preamplifiers, and the gate switching circuit are housed in a shielded metal box. See Appendix C for the receiver head layout. Electromagnetic shielding is important to ensure repeatable electromagnetic deflection. The lens with the chosen focal length mounts on the outside of the box. To facilitate pointing, two mirrors are used to guide the return beam onto the lens. The outgoing 532 nm beam is directed through a concave lens and the General Scanning beam director as shown in Fig. 12. The CCD video camera with an 85 mm lens is mounted above the laser beam director.

Figure 13 shows the targets used for this demonstration. Seven targets of varying shapes were constructed using McMaster-Carr retroreflective tape on black rotatable disks staggered at ranges between 24 m and 51 m. Target sizes were chosen to appropriately fill the Digicon's instantaneous FOV corresponding to the target's range location; sizes vary from 5 m to 10 cm. Two additional small targets were suspended from the ceiling via wires. Of the seven separate FOVs scattered across the FOR, two FOVs include two targets each at different ranges (i.e., nine targets are in seven FOVs).

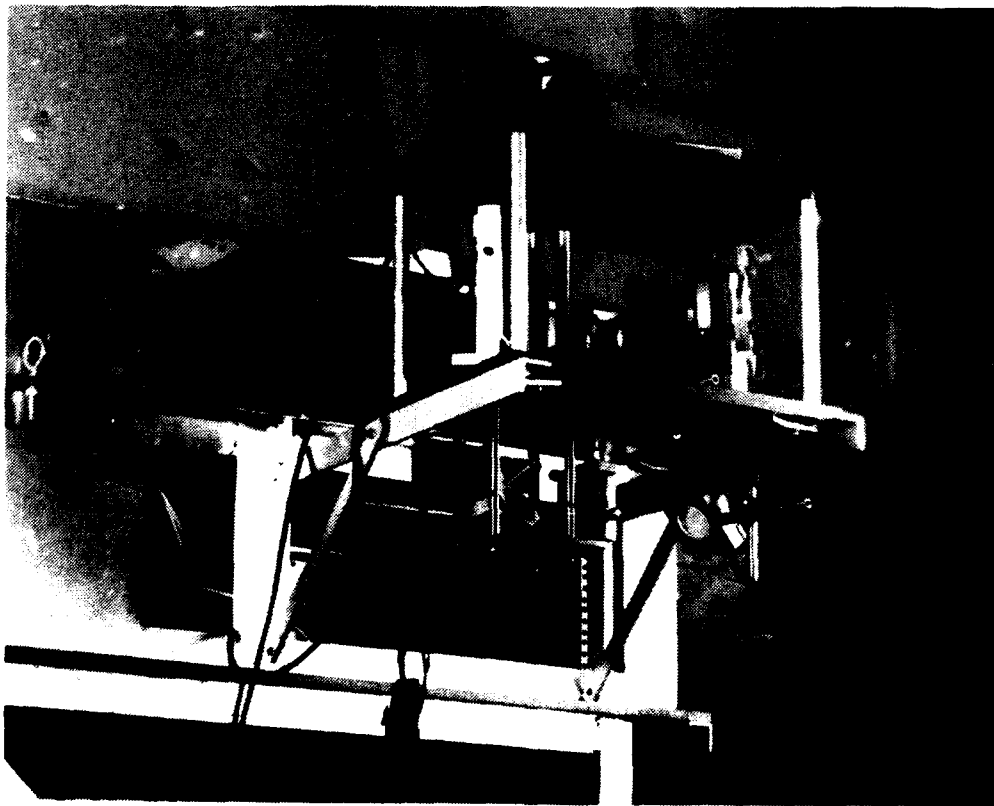


Fig. 11 — Digicon receiver and laser beam director set-up



Fig. 12 — Laser radar transmitter and receiver



Fig. 13 — Retroreflective tape targets located at various distances down a 60 m light tunnel at the NRL Chesapeake Bay Detachment

Enhanced targets constructed of retroreflective tape were selected for determining what ranges might be possible for later outdoor experiments. The retotape was chosen over corner cubes or repoint due to convenience, durability, and eye safety considerations. The corner cubes, for example, produced secondary reflected beams at varying angles.

## 5. EXPERIMENTAL PARAMETERS

The laser beam optics provides a laser beam footprint at the first target that irradiates 99% of the 30.5 cm black disk. A -40 cm focal length lens just before the laser scanner provides a  $1.0^\circ$  divergence, thereby achieving reasonable uniformity over the target area. The intensity variation of the laser beam over the target area is estimated to be less than 20%. The laser scanner mirrors are dielectric-coated so they can withstand the high power density of the 532 nm light. The energy density of each pulse leaving the laser scanner is  $225 \text{ mJ/cm}^2$ . The resulting energy densities striking the targets between 24 m and 51 m vary from  $14 - 62 \text{ } \mu\text{J/cm}^2$ . For this experiment, the number of photoelectrons  $N_{PE}$  striking a single diode of the array is given by the following form of the lidar equation:

$$N_{PE} = \frac{\lambda E_o}{hc} \left[ \frac{\Phi}{\theta R} \right]^2 \left[ \frac{\gamma_1 \gamma_2 \rho \eta}{8} \right] \left[ \frac{f_l}{F} \right]^2, \quad (2)$$



where  $\lambda$  is the laser wavelength,  $E_o$  is the laser output energy (0.2 J),  $h$  is Planck's constant,  $c$  is the speed of light,  $\Phi$  is the instantaneous FOV of one pixel in steradians,  $\theta$  is the transmission beam divergence,  $R$  is the range to the target,  $\gamma_1$  is the transmitter optical transmission (0.443 due to a 50:50 beam splitter, the diverging lens and the scanner mirrors),  $\gamma_2$  is the receiver optical transmission ( $0.45 \times 10^{-3}$  through the telescope, laser filter, and neutral density filter),  $\rho$  is the retroenhancement factor (100),  $\eta$  is photocathode quantum efficiency,  $f_l$  is the focal length of the telescope lens, and  $F$  is the F-stop setting of that lens (i.e., 32). Equation (2) can therefore be reduced to

$$N_{PE} = (8.72 \times 10^{-5}) \left[ \frac{\lambda E_o}{hc} \right] \left[ \frac{\Phi}{\theta R} \right]^2 \left[ \frac{f_l}{F} \right]^2 \quad (3)$$

Correspondingly, the number of photoelectrons hitting one pixel of the diode array varies from 550 to 2550 depending upon range-to-target; this return is well above the 90% detection probability average signal of 15 photoelectrons (assuming a 100 Hz false-alarm rate), yet below saturation (3000 photoelectrons) [7].

The *range gate* width of the Digicon receiver can be adjusted to account for the range window over which targets are dispersed. The receiver was designed to provide a selectable range gate of either 15 m (100 ns) or 150 m (1  $\mu$ s) by using the high-resolution or low-resolution mode of the time-to-digital converters. The placement of the range gate is controlled through a digital delay generator; currently up to 1 ms total delay is available which yields a 150 km range. The total range capability could be extended with additional delay. For this demonstration, the range gate width is set for 150 m, with the gate starting at 17 m from the receiver.

Comparatively, the *amplitude gate* is derived from the time period over which intensity signals are integrated by the analog-to-digital converters (ADC). Intensity signals are integrated over only 20 ns to reduce noise. This 20 ns is significantly shorter than the 1  $\mu$ s corresponding to the 150 m range gate used in this demonstration. The resulting 20 ns (6 m) amplitude gate is positioned through computer control of a second digital delay generator. Thus, for each target in the light tunnel, the location of the amplitude gate varies along with the laser scanner coordinates and the Digicon deflection coordinates.

## 6. RESULTS

Real-time range-per-pixel and intensity-per-pixel images are displayed on a graphics monitor in either of two formats: single FOV display, or multiple FOVs dispersed across the full photocathode FOR. In either format, images can be presented in either gray-scale or pseudocolor.

Figure 14 illustrates two targets in a single FOV display. The screen is divided into four quadrants with range-per-pixel and intensity-per-pixel images shown on the left. Note that the range image shows two distinct targets at dramatically different ranges, whereas the intensity image shows only the unblocked portion of the further target. This is because the range gate is set to encompass any targets between 17 and 167 m, while the amplitude gate is only 20 ns (6 m) wide and is set at 265 ns to view the target at 51 m. The range gray-scale is currently set to display targets between 10 and 60 m; the intensity scale is represented in terms of ADC units from 0 - 2047. The upper right quadrant is a three-dimensional illustration of the target location. The target position, size, and the deflection angle required are indicated. The z-coordinate is the maximum range returned from any of the 64 pixels. The lower-right depicts the azimuth, elevation and range-to-target as a function of time; this strip chart representation is useful for small targets moving within the FOV.

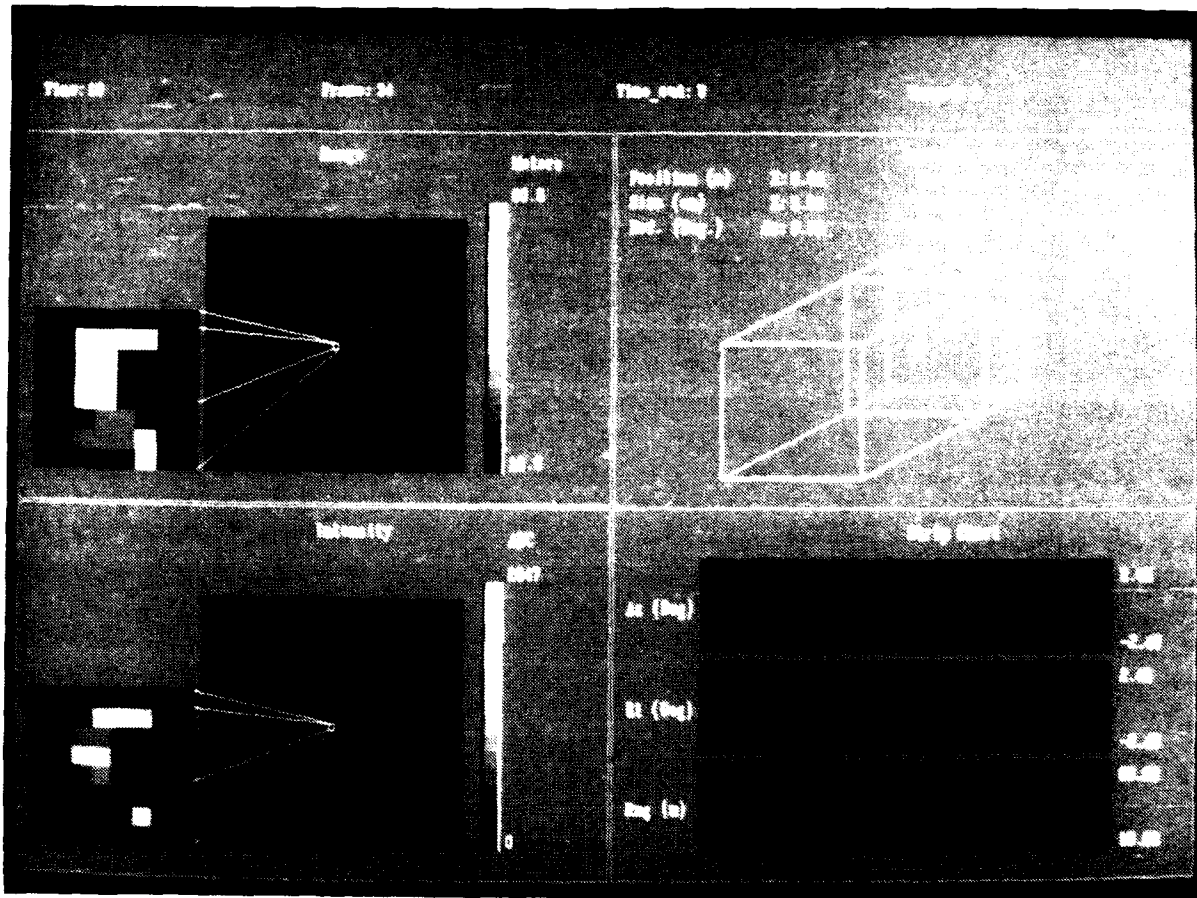


Fig. 14 — Single FOV display with a range-per-pixel image, an intensity-per-pixel image, and three-dimensional position measurement

Figures 15 through 17 visualize rapid multiple retargeting on the full photocathode display. Seven FOVs are evident across the full photocathode display. Figure 15 depicts pseudocolor range images where the  $8 \times 8$  array footprints are shown actual size relative to the FOR. The size of the FOV on the display is controllable by the computer operator through a software command. The usual mode of operation is seen in Fig. 16 where images are magnified three times for ease of interpretation. Nine distinct range images are visible within seven FOVs scattered throughout the FOR. The pseudocolor display clearly illustrates the multiple targets within one FOV. Position, size, and deflection data are documented for each FOV with the z-coordinate representing the range to the furthest target. The range resolution is better than 1 m. For comparison, magnified intensity images are shown in Fig. 17. These gray-scale images depict only one target per FOV because of the narrow amplitude gate.

The rapid multiple retargeting experiment can be performed in two ways: first, with the graphics display actively displaying in real time, and second, with the data being stored in the computer memory and later played back on the computer screen. The real-time graphics display limits the demonstration to 5 Hz. With the display turned off, which is a condition more closely related to an operational system, 15 Hz multiple retargeting is easily achieved. It is important to note that even 15 Hz is an artificial limitation on the speed because of the use of an off-the-shelf processor with a clock speed of 10 MHz. A faster processor tailored to the task would have no trouble reaching 50 targets/second. Table 3 lists the performance parameters of the Digicon receiver.



**Fig. 15 — Multiple FOVs across the photocathode showing actual array footprint size relative to the full photocathode footprint (range images)**

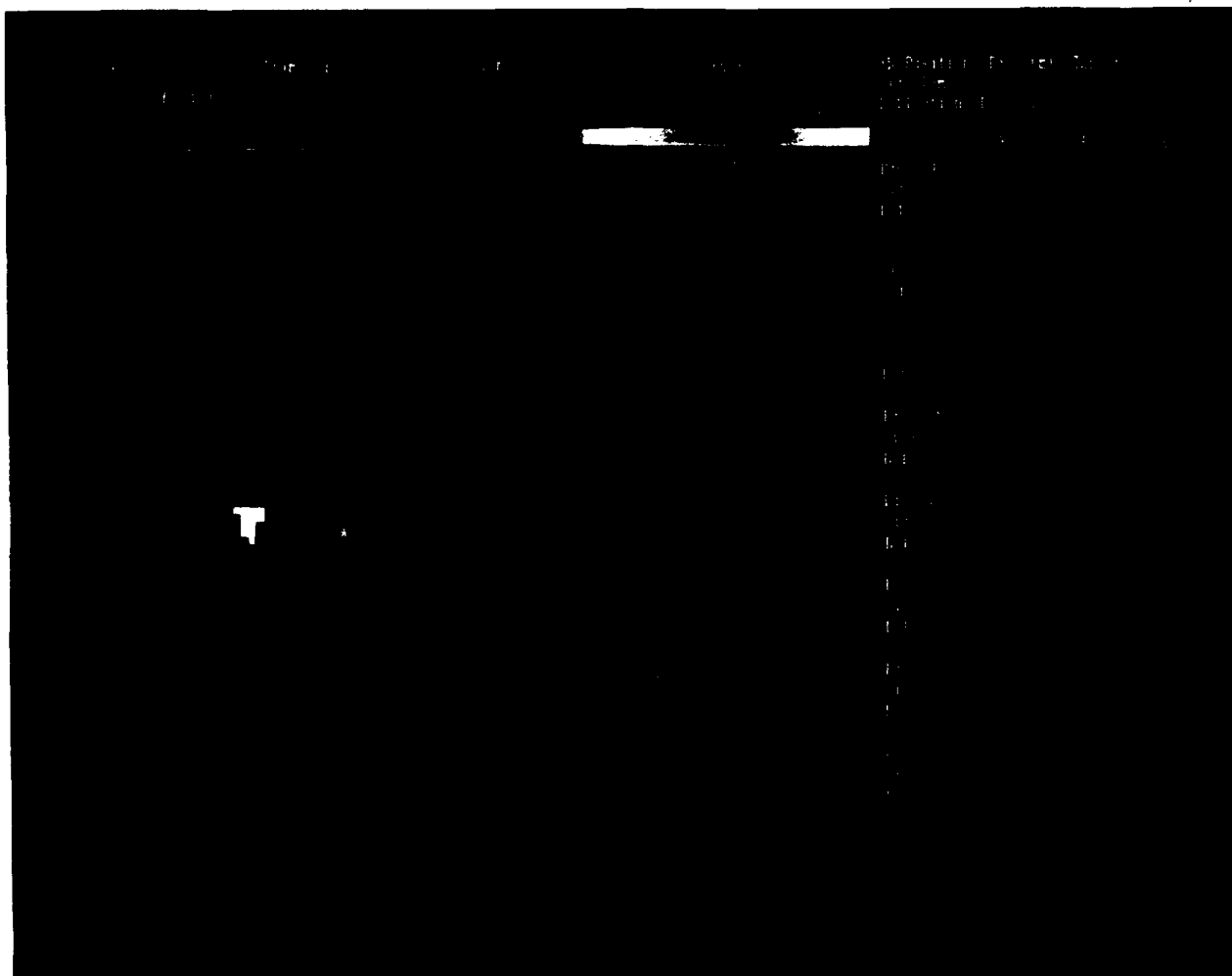


Fig. 16 — Multiple range images across the photocathode. These FOVs are magnified three times for ease of viewing.

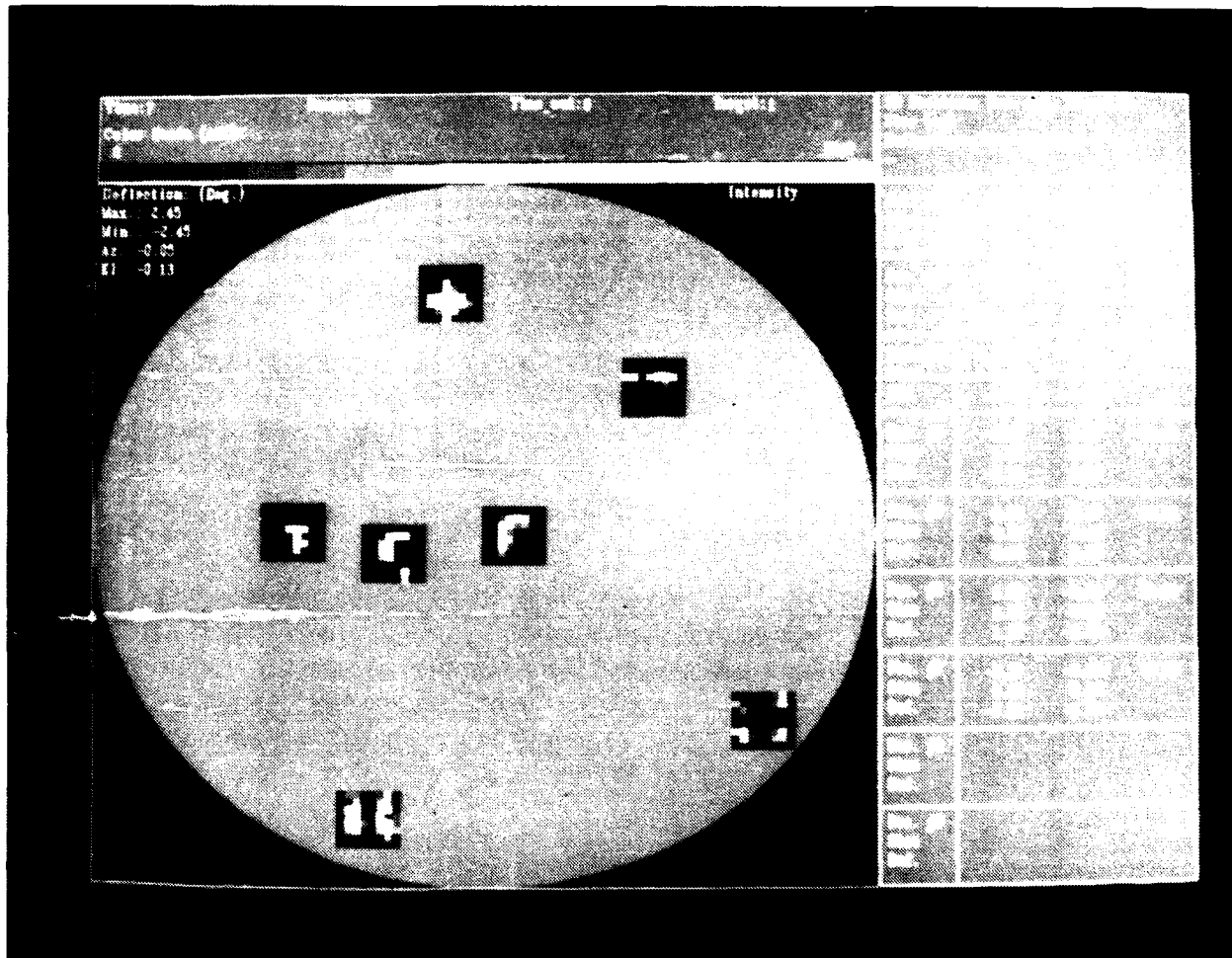


Fig. 17 — Multiple intensity images across the photocathode. These FOVs are magnified three times for ease of viewing.

Table 3 — Digicon Performance Parameters

	Digicon Receiver Demonstrated Parameters	Digicon-Limited Performance Parameters
Range Resolution	< 1 m	5 cm*
Pixel Subtense	1.25 mrad (80 mm telescope)	**
Deflection Speed	15 Hz	~ 200 Hz
Maximum Image Distortion over the Photocathode	< 7 pixels	***

\*20 PE signal, pulse risetime < 3 ns, time resolution 0.3 ns, false-alarm rate <  $10^6/\mu\text{s}$ .

\*\*Depends on the focal length of the telescope.

\*\*\*Remappable.

The  $8 \times 8$  - pixel prototype Digicon receiver can also be used to simulate the anticipated performance of the next generation Digicon tube under construction with a  $16 \times 16$  diode array. Figure 18 illustrates the  $16 \times 16$  array footprint created by rapidly retargeting between the four quadrants of a  $16 \times 16$  - pixel image. The  $16 \times 16$  array footprint of Fig. 18 can be compared to the  $8 \times 8$  array footprint of Fig. 15. (Note that this simulation assumes zero magnification as is the case on the initial  $8 \times 8$  Digicon tube. Future Digicon tubes are planned to have magnification capability.)

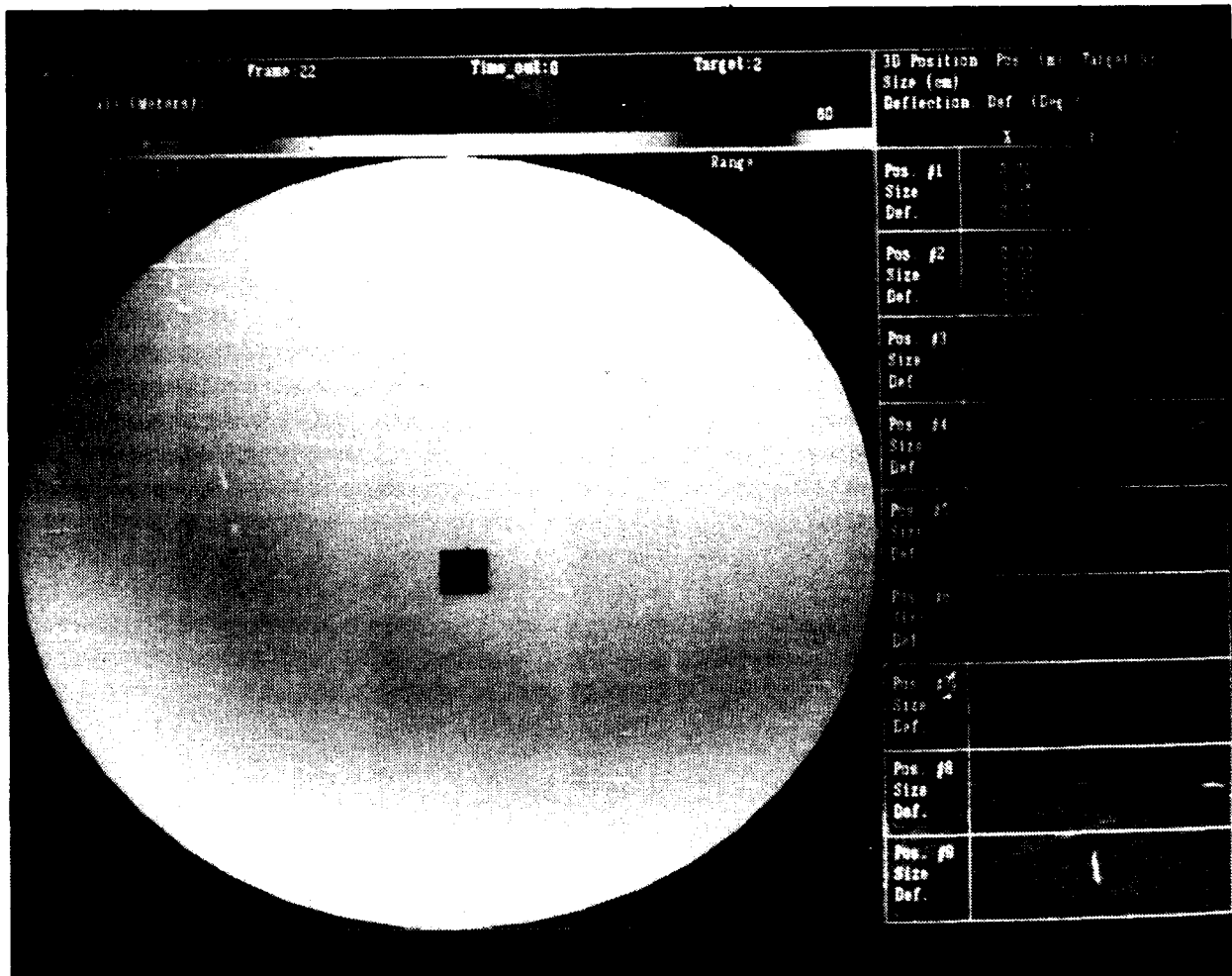


Fig. 18 — Simulation of a  $16 \times 16$  Digicon tube showing anticipated array footprint size relative to the full photocathode footprint

Distortion effects of the Digicon receiver have been investigated using a 1.2 m square black target board with 7.9 mm circular retroreflective tape targets (located to within  $25 \mu\text{m}$  accuracy) positioned at a 23.5 m range to map out the photocathode. With a 350 mm lens in front of the Digicon tube, these targets are slightly larger than one resel (defined as the footprint of one pixel at that range, or 6.7 mm). Thus, the location of each target is determined to the nearest  $0.01^\circ$  by aligning the center 4 pixels of the  $8 \times 8$  array on the target of interest. The experimental data represented by crosses in Fig. 19 has been translated  $0.13^\circ$  in the x axis and  $0.17^\circ$  in the y axis to center the experimental data on the target board coordinate frame of reference. (Obviously, alignment of the target board in the Digicon FOR was not precise.) The experimental map of the target board is rotated; this is due to imperfect rotational alignment of the Digicon tube with respect to the target board. In Fig. 20, the experimental data has been rotated clockwise  $7.84^\circ$  about the center to illustrate only distortion mapping effects across the

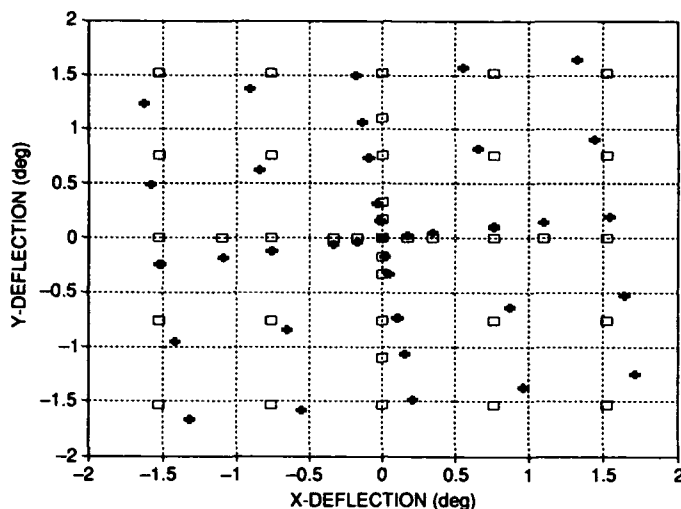


Fig. 19 — Target board mapping data across the Digicon photocathode. Squares indicate actual target locations; crosses mark corresponding locations of Digicon images. Obviously, a rotational correction is needed.

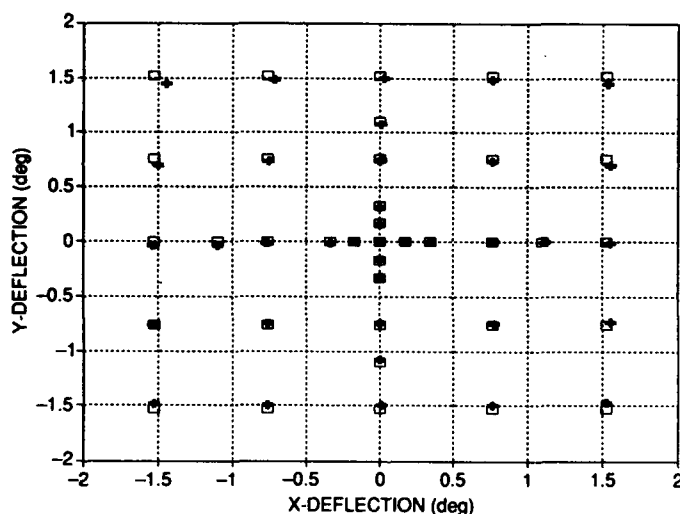


Fig. 20 — Distortion mapping effects across the Digicon photocathode. (The experimental data of Fig. 19 has been rotated  $7.84^\circ$  clockwise.) Squares indicate actual target locations; crosses mark corresponding locations of Digicon images.

photocathode. Figure 20 illustrates that the pointing accuracy varies with deflection angle. For example, within  $0.5^\circ$  deflection, the pointing accuracy is  $> 99\%$  (error  $< 0.005^\circ$ ) whereas, on the x axis at  $1.5^\circ$  deflection, the pointing accuracy is  $98\%$  ( $0.03^\circ$  error). The worst case in the upper left corner at  $(-1.5^\circ, 1.5^\circ)$  shows a  $5\%$  pointing error. Therefore, in addition to anticipated translational and rotational corrections due to tube alignment accuracy, a conformal mapping is needed to correct for these distortion effects increasingly evident near the photocathode perimeter.

In addition to distortion effects, thermal drift effects of the Digicon receiver have been observed. Figure 21 shows target board mapping data collected over a 4 hr period. The data was collected in the

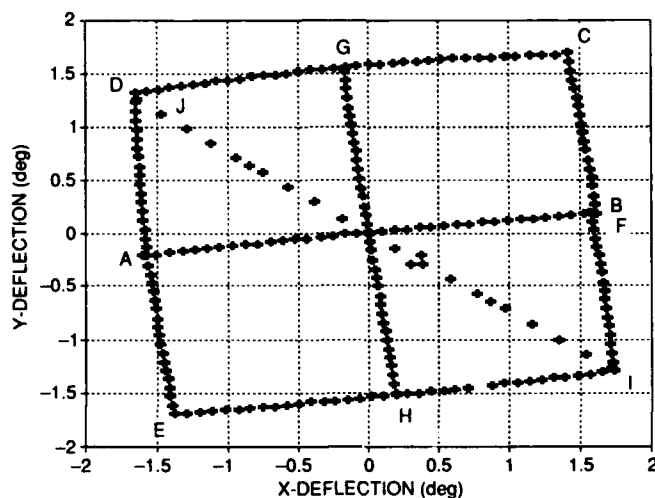


Fig. 21 — Target board mapping data showing thermal drift over the 4 hr data collection period. Data collection begins at point A, continues horizontally to B, then follows around the complete square to F; subsequently, data collection continues along lines GH and IJ.

order indicated by the alphabetical letters. Significant drift is observed at points A and B; as time progresses, less deflection is required to view a target off center. Equipment warm-up times of 2 hr were generally required to avoid thermal drifts greater than  $0.1^\circ$ ; however, even after lengthy warm-up periods, thermal drifts of  $0.03^\circ$  to  $0.06^\circ$  were frequently observed. Certainly this thermal drift problem merits further investigation to improve pointing accuracy. Photocathode distortion is to blame for the pin-cushion effects in Fig. 21.

## 7. FUTURE DIRECTIONS

Future directions of interest for this short wavelength laser radar include

- completion of the acquisition and handoff capability,
- tracking,
- outdoor demonstrations, and
- completed development of a  $16 \times 16$  array Digicon tube with magnification.

The acquisition software to acquire a target via the video camera mounted above the Digicon is already implemented on a workstation. See Appendix D for acquisition and handoff programs. The programs available either select targets through the computer mouse control or scan for return above a set threshold; then, the appropriate coordinate and frame-of-reference transformations are computed, and target coordinates for direction of the laser beam and the Digicon FOV are output through a parallel port. The hardware handshake from the workstation's parallel port to the microcomputer, however, is incomplete at this time. Software to enable tracking of moving targets across the FOR is also required.

Outdoor experiments were originally planned to take place over the Chesapeake Bay using boats and/or planes as targets at ranges from 0.4 - 2 km. Depth of field could thereby be demonstrated with an extended target (i.e., a boat) turning in the water yielding varying range returns along its length. Plans to track 12-gauge shotgun slugs or clay targets have also been studied. See Appendix E for planned outdoor experimental parameters. Appendix F is the laser safety analysis required for all planned outdoor and indoor experiments.



As a follow-up to this first prototype Digicon receiver, a  $16 \times 16$  array Digicon tube with magnification of 0.25 to 40 has been designed and tested in a demountable configuration. The concept for this advanced Digicon detector with deflection and magnification is described in Fig. 22. The first stage of the tube is identical to the initial prototype Digicon of Fig. 2. The second stage uses a magnetic lens to reimage and magnify the first stage electron image onto the diode array at the rear of the second stage. The spatial resolution is thereby increased by reducing the effective pixel size at the photocathode. The next step in the development of this system would be this improved Digicon receiver with redesigned processing electronics to handle the 256 parallel return signals.

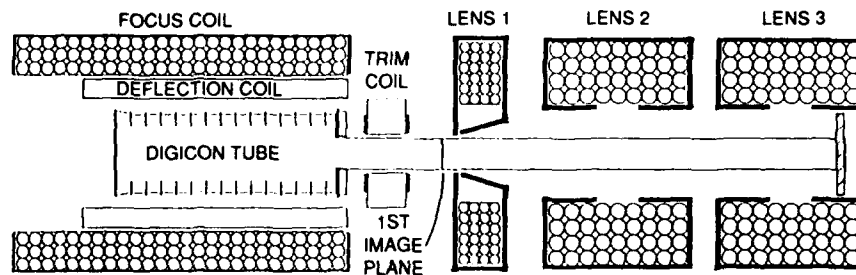


Fig. 22 — Advanced Digicon (two-stage) with deflection and magnification of the electron image

## 8. SUMMARY

A Digicon laser radar receiver operating at 532 nm has demonstrated several key features critical for discrimination and targeting: 1) rapid multiple retargeting over an extended FOR, 2) display of  $8 \times 8$  range-per-pixel and intensity-per-pixel images for each laser shot, and 3) three-dimensional position measurement for each target. This receiver system currently operates at 15 Hz to direct-detect multiple targets dispersed over ranges up to 61 m. Work planned to improve upon this initial prototype receiver includes the completion of an acquisition and handoff capability, tracking, long-range experiments ( $\sim 1$  km) and the development of a  $16 \times 16$  array Digicon tube with magnification.

## 9. ACKNOWLEDGMENTS

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## Appendix A

### COMPUTER-TO-LASER INTERFACE

A computer-to-laser interface board was constructed to enable control of the laser firing from the computer. Figure A1 is a schematic of the laser interface board. Ribbon cable connections from the Burr-Brown rate generator module within the laser radar processing electronics to the laser interface board are as follows:

PIN	DESCRIPTION
4	BB Timer Ch 0 Gate Input (Not Used)
6	BB Timer Ch 0 Clock Input
8	BB Timer Ch 0 Output
10	BB Timer Ch 1 Gate Input
12	BB Timer Ch 1 Clock Input
14	BB Timer Ch 1 Output
16	BB Timer Ch 2 Gate Input (Not Used)
18	BB Timer Ch 2 Clock Input
20	BB Timer Ch 2 Output
22	BB Timer Ch 3 Gate Input
24	BB Timer Ch 3 Clock Input
26	BB Timer Ch 3 Output
28	BB Timer Rate Generator Output

BB Timer Ch 0	Generates 30 Hz Laser CHARGE signal Software set maximum count Rate Generator provides Clock Input Automatically resets after max count
BB Timer Ch 1	Generates 30 Hz Laser FIRE signal Signal delayed 27 ms from CHARGE Software set maximum count Gate Input from CHARGE starts count Rate Generator provides Clock Input
BB Timer Ch 2	Generates $(30/N)$ Hz to Enable Q-SWITCH signal $N > 1$ set by software Clock comes from FIRE signal
BB Timer Ch 3	Generates $(30/N)$ Hz Q-SWITCH signal Signal delayed 3.4 ms from FIRE Rate Generator provides Clock Input

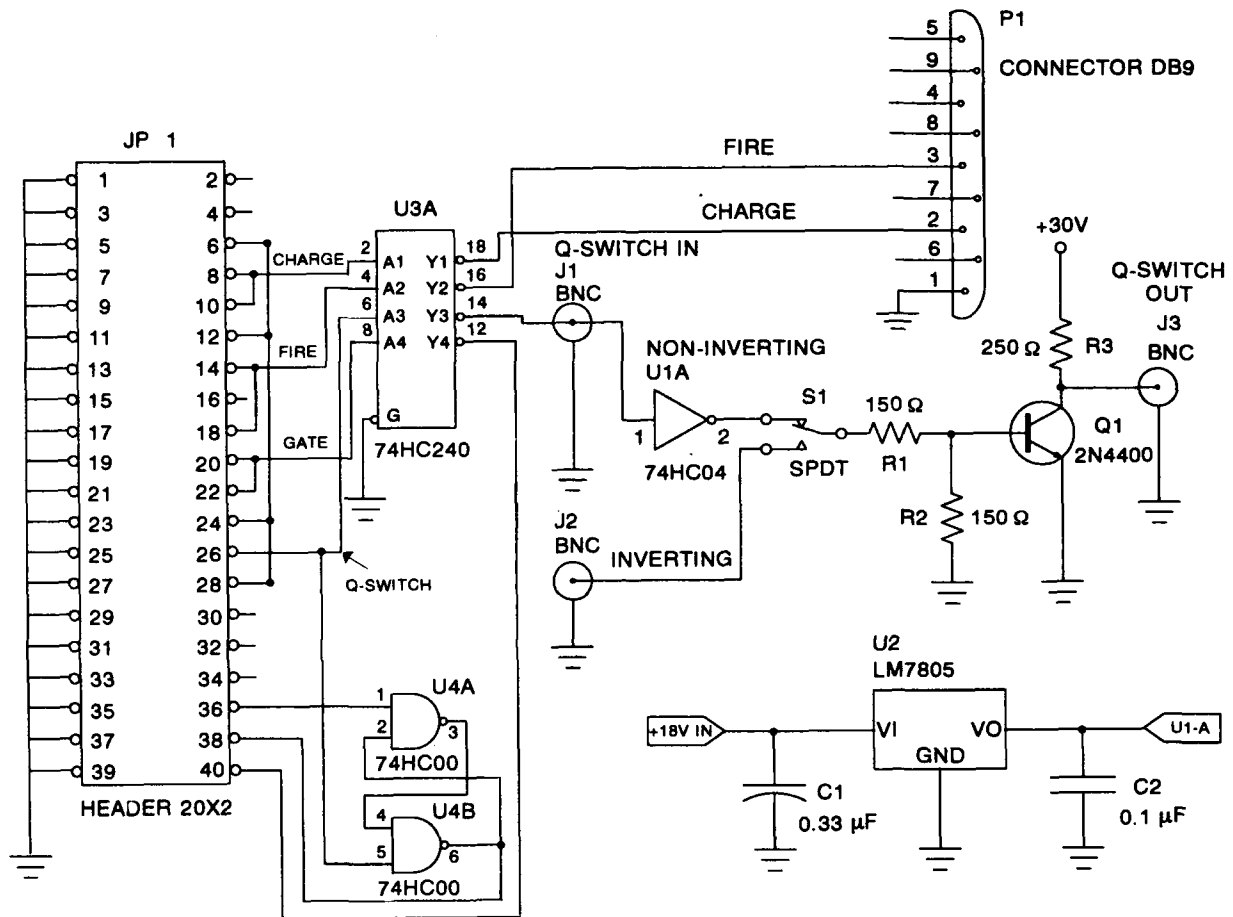


Fig. A1 — Schematic of the laser interface board to control laser firing from the computer

## Appendix B

### DG PARALLEL FIX

The "DG-Parallel Fix" described in Fig. B1 was required to achieve successful communication between the 80286 computer (PC) parallel printer port and the parallel input port on the General Scanning beam director. Without this fix, "paper out" error messages would be sent to the computer, thereby ceasing further data transfer.

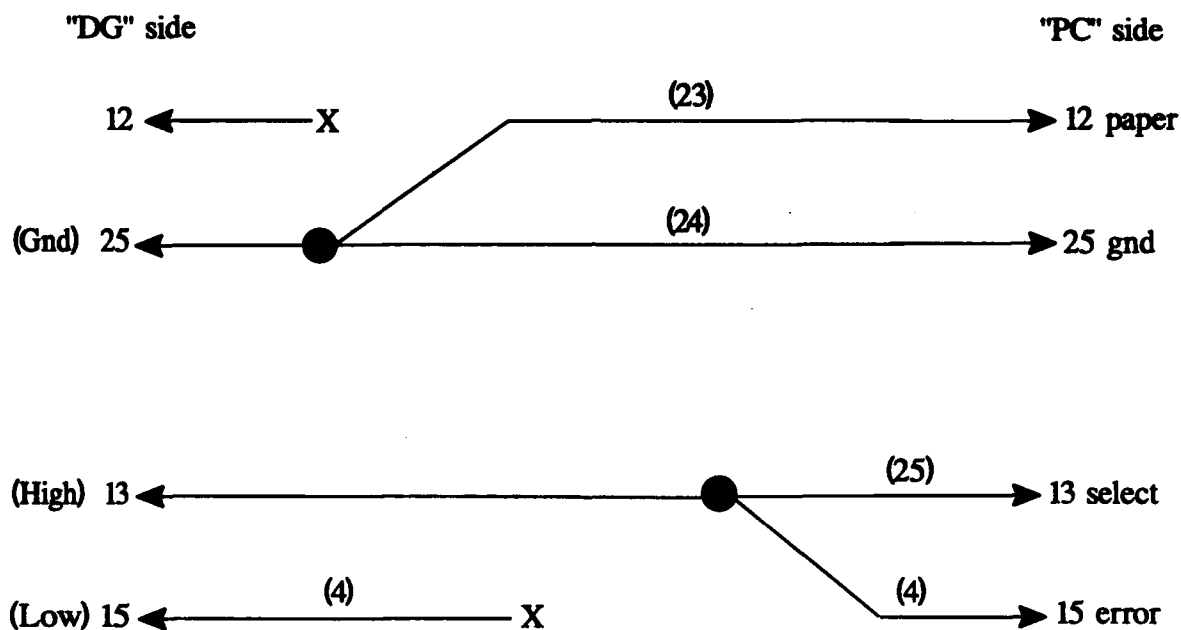


Fig. B1 — DG parallel fix for scanner - PC interface

## Appendix C

### RECEIVER HEAD LAYOUT

The Digicon receiver head layout is illustrated in Fig. C1. The Hasselblad telescope lens is mounted to the exterior of the metal box 7.5 cm away from the Digicon photocathode.

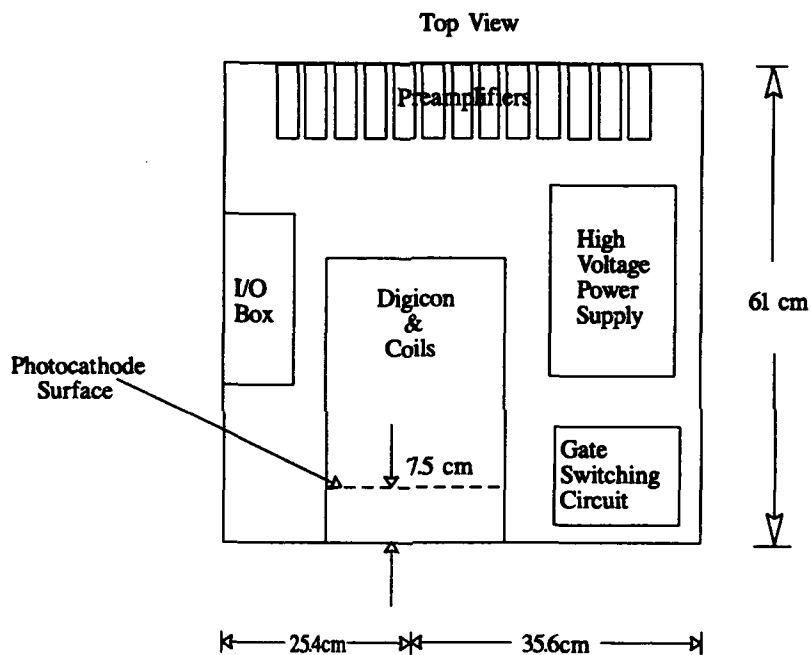


Fig. C1 — Digicon receiver head layout

## Appendix D

### ACQUISITION AND HANDOFF PROGRAMS

Three acquisition and handoff programs operating on a Sun 4/370 workstation with Innovision Corp. IC200 software and a frame-grabber board follow. Significant contributions to these routines were made by Dr. Doug Benson of Innovision Corp., Research Triangle Park, NC.

The first program, *target.c*, allows the computer controller to choose targets within the CCD camera's FOV through Innovision's cursortool software. A desired target list can be generated via window buttons (ADD and DELETE); this list can then be displayed (LIST), saved (SAVE), loaded (LOAD), cleared (CLEAR), or sent to the laser scanner (RUN).

The second and third programs, *follow.c* and *temp.c*, were designed for the planned long-range experiments described in Appendix E. The programs involve scanning the FOV of the CCD camera, finding the location of a target (after thresholding with the Innovision software), and directing the laser scanner to that location. Tracking capability is included. The primary concern here is speed, particularly for the proposed shotgun slug tracking experiments. The *follow.c* program scans a full field as defined from the command line (maximum size of  $512 \times 485$  pixels) with the lower left corner defined as pixel (0,0), whereas *temp.c* scans a  $100 \times 100$  pixel area with the lower left corner at pixel (200,200). *Temp.c* also includes a clocking capability to time the acquisition process. Both of these routines or variations thereof would be used in finding optimum parameters for acquisition and handoff for a given experiment.

/\*

target.c

July 16, 1990

S. Hiser &amp; G. Roe

This target acquire routine enables one to choose a target within a CCD camera's IFOV via Innovision software: cursortool. A list of targets is generated via window buttons (add and delete), which can be displayed, saved, loaded, or sent to the laser scanner (run).

\*/

#include &lt;stdio.h&gt;

#include &lt;suntool/sunview.h&gt;

#include &lt;suntool/panel.h&gt;

#include &lt;string.h&gt;

#define PROX 15

/\* Proximity in pixels for deleting targets \*/

#define MAXTARG 20

/\* Maximum number of targets \*/

/\* Declarations \*/

Frame frame;

Panel panel;

Panel\_item run\_button;

Panel\_item add\_button, delete\_button, quit\_button, number\_message;

Panel\_item disp\_message, list\_button, save\_button, response\_message;

Panel\_item load\_button, clear\_button, file\_input;

Pixwin \*pw;

Pixrect \*add\_image, \*delete\_image, \*list\_image, \*save\_image, \*quit\_image;

Pixrect \*run\_image, \*load\_image, \*clear\_image;

Icon icon;

char \*tn, \*rsp, \*fname;

static char addrsp[] = "TARGET ADDED"; /\* Responses that are \*/

static char delrsp[] = "TARGET DELETED"; /\* displayed when \*/

static char listrsp[] = "TARGETS LISTED"; /\* certain buttons are \*/

static char saversp[] = "TARGET LIST SAVED"; /\* pushed. \*/

static char clearrsp[] = "LIST CLEARED";

static char loadrsp[] = "LIST LOADED";

static char errorrsp[] = "NO FILE FOUND";

static char baddrsp[] = "NO TARGET FOUND";

static char norsp[] = "";

static char filename[] = "targlist"; /\* Default file name \*/

char targnum[3];

int ntargs; /\* Number of targets \*/

int x[MAXTARG], y[MAXTARG]; /\* Target Coordinates \*/



```

static short      targ_image[256] = {
#include </home/hiser/handoff/targ.icon>
};mpr_static(targ, 64, 64, 1, targ_image);

/*
static short      targ_image[256] = {
#include </home/roe/programs/targ.icon>
};mpr_static(targ, 64, 64, 1, targ_image);
*/

/* MAIN PROGRAM      */
main()
{
void      add(), delete(), list(), save(), quit(), init_panel(), display(), run();
void      load(), clear();
int cotran(), cotranbs(), itoa(), reverse();

rsp = &norsp[0];
tn = &targnum[0];
fname = &filename[0];
ntargs = 0;
itoa(ntargs, targnum);
icon = icon_create(ICON_IMAGE, &targ, 0);

init_panel();

window_main_loop(frame);
exit(0);
}                                /* END MAIN */

/* INITIALIZE PANEL      */
void init_panel()
{
frame = (Frame) window_create(NULL,FRAME, FRAME_LABEL, "TARGET",
FRAME_ICON, icon,
0);
if (frame == (Frame) NULL) {
fprintf(stderr, "SunView not available\n");
exit(1); }
}

```

```

panel = (Panel) window_create(frame,PANEL, 0);
pw = (Pixwin *) window_get(panel, WIN_PIXWIN);

add_image = (Pixrect *) panel_button_image(panel, "Add Target", 0, 0);
delete_image = (Pixrect *) panel_button_image(panel, "Del. Target", 0, 0);
quit_image = (Pixrect *) panel_button_image(panel, "Quit", 0, 0);
list_image = (Pixrect *) panel_button_image(panel, "Disp. List", 0, 0);
save_image = (Pixrect *) panel_button_image(panel, "Save List", 0, 0);
run_image = (Pixrect *) panel_button_image(panel, "Run ", 0, 0);
load_image = (Pixrect *) panel_button_image(panel, "Load List", 0, 0);
clear_image = (Pixrect *) panel_button_image(panel, "Clear List", 0, 0);

add_button = (Panel_item) panel_create_item(
    panel, PANEL_BUTTON,
    PANEL_LABEL_IMAGE, add_image,
    PANEL_NOTIFY_PROC, add,
    PANEL_ITEM_Y, ATTR_ROW(0),
    PANEL_ITEM_X, ATTR_COL(0),
    0);

delete_button = (Panel_item) panel_create_item(
    panel, PANEL_BUTTON,
    PANEL_LABEL_IMAGE, delete_image,
    PANEL_NOTIFY_PROC, delete,
    PANEL_ITEM_Y, ATTR_ROW(1),
    PANEL_ITEM_X, ATTR_COL(0),
    0);

list_button = (Panel_item) panel_create_item(
    panel, PANEL_BUTTON,
    PANEL_LABEL_IMAGE, list_image,
    PANEL_NOTIFY_PROC, list,
    PANEL_ITEM_Y, ATTR_ROW(0),
    PANEL_ITEM_X, ATTR_COL(14),
    0);

save_button = (Panel_item) panel_create_item(
    panel, PANEL_BUTTON,
    PANEL_LABEL_IMAGE, save_image,
    PANEL_NOTIFY_PROC, save,
    PANEL_ITEM_Y, ATTR_ROW(0),
    PANEL_ITEM_X, ATTR_COL(27),
    0);

```

```
run_button = (Panel_item) panel_create_item(
    panel, PANEL_BUTTON,
    PANEL_LABEL_IMAGE, run_image,
    PANEL_NOTIFY_PROC, run,
    PANEL_ITEM_Y, ATTR_ROW(0),
    PANEL_ITEM_X, ATTR_COL(39),
    0);
```

```
load_button = (Panel_item) panel_create_item(
    panel, PANEL_BUTTON,
    PANEL_LABEL_IMAGE, load_image,
    PANEL_NOTIFY_PROC, load,
    PANEL_ITEM_Y, ATTR_ROW(1),
    PANEL_ITEM_X, ATTR_COL(27),
    0);
```

```
clear_button = (Panel_item) panel_create_item(
    panel, PANEL_BUTTON,
    PANEL_LABEL_IMAGE, clear_image,
    PANEL_NOTIFY_PROC, clear,
    PANEL_ITEM_Y, ATTR_ROW(1),
    PANEL_ITEM_X, ATTR_COL(14),
    0);
```

```
quit_button = (Panel_item) panel_create_item(
    panel, PANEL_BUTTON,
    PANEL_LABEL_IMAGE, quit_image,
    PANEL_NOTIFY_PROC, quit,
    PANEL_ITEM_Y, ATTR_ROW(1),
    PANEL_ITEM_X, ATTR_COL(39),
    0);
```

```
disp_message = (Panel_item) panel_create_item(
    panel, PANEL_MESSAGE,
    PANEL_LABEL_STRING, "# of Targets:",
    PANEL_ITEM_Y, ATTR_ROW(3),
    PANEL_ITEM_X, ATTR_COL(0),
    0);
```

```
number_message = (Panel_item) panel_create_item(
    panel, PANEL_MESSAGE,
    PANEL_LABEL_STRING, tn,
    PANEL_ITEM_Y, ATTR_ROW(3),
    PANEL_ITEM_X, ATTR_COL(15),
    0);
```

```

response_message = (Panel_item) panel_create_item(
    panel, PANEL_MESSAGE,
    PANEL_LABEL_STRING, rsp,
    PANEL_ITEM_Y, ATTR_ROW(3),
    PANEL_ITEM_X, ATTR_COL(21),
    0);

file_input = (Panel_item) panel_create_item(
    panel, PANEL_TEXT,
    PANEL_LABEL_STRING, "Filename: ",
    PANEL_VALUE, fname,
    PANEL_VALUE_DISPLAY_LENGTH, 20,
    PANEL_ITEM_Y, ATTR_ROW(4),
    PANEL_ITEM_X, ATTR_COL(0),
    0);

window_fit(panel);
window_fit(frame);
}                /* END INITIALIZE PANEL */

/* ADD TARGET */
void add()
{
    FILE *fp;

    if (ntargs < MAXTARG)
    {
        if ((fp = fopen("/usr/icdev/setcur.dat", "r")) != NULL)
        {
            fscanf(fp, "%d %d", &x[ntargs], &y[ntargs]);
            printf("ADDED TARGET # = %d X = %d Y = %d\n", ntargs + 1,
                x[ntargs], y[ntargs]);
            fclose(fp);
        }
        else
        {
            printf("Could not open the file \"/usr/icdev/setcur.dat\".\n");
            return;
        }
    }
    else

```

```

{
printf ("TOO MANY TARGETS! - NOT ALLOWED MORE THAN 20 TARGETS.\n");
return;
}

ntargs++;
itoa(ntargs, targnum);
panel_set(number_message, PANEL_LABEL_STRING, tn, 0);
rsp = &addrsp[0];
display();
return;
}                /* END ADD */

/* DELETE TARGET */
void delete()
{
int i,j,a,b;
int flag = 0;
FILE *fp;

if (ntargs == 0) return;

/* Read in approximate location of target that should be deleted */
if ((fp = fopen ("/usr/icdev/setcur.dat", "r")) != NULL)
{
fscanf (fp, "%d %d", &a, &b);
printf ("Selected to delete X = %d Y = %d\n", a,b);
fclose (fp);
}
else
{
printf ("Could not open the file \"/usr/icdev/setcur.dat\".\n");
return;
}

/* Compare (a,b) with (x[i], y[i]) to find the appropriate target to delete */
for (i=0; i < ntargs; i++)
{
if ((abs (a - x[i]) < PROX) && (abs (b - y[i]) < PROX))
{
printf ("Target deleted at X = %d Y = %d\n", x[i], y[i]);
}
}
}

```

```

        for (j = i; j < ntargs; j++)
        {
            x[j] = x[j+1];
            y[j] = y[j+1];
        }
        flag = 1;
        break;
    }
}
if (!flag)
{
    rsp = &baddelrsp[0];          /* No target found to delete */
    display();
    return;
}

```

```

ntargs--;
itoa(ntargs, targnum);
panel_set(number_message, PANEL_LABEL_STRING, tn, 0);
rsp = &delrsp[0];
display();
return;
}          /* END DELETE */

```

/\* LIST TARGETS \*/

```

void list()
{
    int i;
    printf ("\nTARGET # X      Y\n\n");
    for (i=0; i < ntargs; i++)
    {
        printf (" %d      %d      %d\n", i+1, x[i], y[i]);
    }
}

```

```

rsp = &listrsp[0];
display();
return;
}          /* END LIST */

```

/\* SAVE TARGET LIST \*/

```

void save()
{
    int i;
    FILE *fp;
}

```

```

/* Saves target list to file as real numbers */
strcpy(filename, (char *)panel_get_value(file_input));
fp = fopen (filename, "w"); /* write mode */
for (i=0; i < ntargs; i++) {
    fprintf (fp, "%d %d\n", x[i], y[i]);
}
fclose (fp);

rsp = &saversp[0];
display();
return;
} /* END SAVE */

/* LOAD TARGET LIST */
void load()
{
    int i=0;
    FILE *fp;

    strcpy(filename, (char *)panel_get_value(file_input));
    if ((fp = fopen (filename, "r")) == NULL)
    {
        rsp = &errorrsp[0]; /* No file found */
        display();
        return;
    }
    while(feof(fp) == 0) /* Load list of targets */
    {
        fscanf(fp, "%d %d", &x[i], &y[i]);
        i++;
    }
    fclose(fp);
    ntargs = i-1;
    itoa(ntargs, targnum);
    panel_set(number_message, PANEL_LABEL_STRING, tn, 0);
    rsp = &loadrsp[0];
    display();
    return;
}

```

```

/* CLEAR TARGET LIST */
void clear()
{
    ntargs = 0;
    itoa(ntargs, targnum);
    panel_set(number_message, PANEL_LABEL_STRING, tn, 0);
    rsp = &clearrsp[0];
    display();
    return;
}

/* RUN */
void run()
{
    float ary=6.6, arx=8.8, f=12.5, npy=485., npx=512.; /* CCD camera constants */
    FILE *fp;
    int i,j,k;
    int xsc, ysc;
    char xstr[MAXTARG][6], ystr[MAXTARG][6];

    for (i=0; i < ntargs; i++)
    {
        xsc = cotranbs ((float)x[i],npx,arx,f); /* Coordinate Transforms */
        ysc = cotran ((float)y[i],npy,ary,f);

        itoa (xsc, xstr[i]);      /* Integer to String conversions */
        itoa (ysc, ystr[i]);

        /* printf ("X = %d \nY = %d \n", x[i], y[i]);
        printf ("XSC = %d \nYSC = %d \n", xsc, ysc);
        printf ("XSTR = %s \nYSTR = %s \n", xstr[i], ystr[i]); */
    }

    /* Output through ALM serial port to the laser scanner */

    fp = fopen ("/dev/mcpp0", "w"); /* write mode */

    fprintf (fp, "JX%s\nJY%s\nEC\n", xstr[0], ystr[0]);
    for (j=1; j < ntargs; j++)
    {
        fprintf (fp, "JX%s\nJY%s\n", xstr[j], ystr[j]);
    }
    for (k=0; k < 100; k++)
    {
        fprintf (fp, "EX\n");
    }
    fclose (fp);
} /* END RUN */

```



```

/* QUIT PROGRAM      */
void quit()
{
    exit(0);
}

```

```

/* DISPLAY RESPONSE  */
void display()
{
    int    i;

```

```

    panel_set(response_message, PANEL_LABEL_STRING, rsp, 0);
    rsp = &norsp[0];
    for(i=0; i < 800000; i++);
    panel_set(response_message, PANEL_LABEL_STRING, rsp, 0);
    return;
}

```

```

/* Coordinate Transformation from CRT Screen to the Laser Scanner */
cotran (cc,np,ar,f)
float ar,f,np,cc;
{
    float sc;
    sc = 32767 * (1 - (2.475 * (cc/np - 0.5) * ar/f)) + 0.5;
    return ((int)sc);
}
/* END COTRAN*/

```

```

/* Coordinate Transformation from CRT Screen to the Laser Scanner */
/* WITH MIRROR IMAGE SHIFT DUE TO BEAM SPLITTER BEFORE CCD CAMERA */
cotranbs (cc,np,ar,f)
float ar,f,np,cc;
{
    float sc;
    sc = 32767 * (1 - (2.475 * ((np-cc)/np - 0.5) * ar/f)) + 0.5;
    return ((int)sc);
}
/* END COTRANBS */

```

```

/* Integer to a String Conversion Routine */
itoa ( n, s)
    int n;
    char s[];
{
    int i, sign;

    if ((sign = n) < 0) /* record sign */
        n = -n;
    i = 0;
    do { /* generate digits in reverse order */
        s[i++] = n % 10 + '0'; /* get next digit*/
    } while ((n /= 10) > 0); /* delete it*/

    if (sign < 0)
        s[i++] = '-';
    s[i] = '\0';
    reverse (s);
} /*      END ITOA      */

```

```

/* Reverse String s in Place */
reverse (s)
    char s[];
{
    int c, i, j;

    for (i = 0, j = strlen(s)-1; i < j; i++, j--)
    {
        c = s[i];
        s[i] = s[j];
        s[j] = c;
    }
} /*      END REVERSE*/

```

```

/* follow.c      */
/*
                                June 8, 1990
                                S. Hiser & D. Benson
*/
/* Program to scan the FOV of a CCD camera, find the location of a target (after thresholding), and
   direct the laser scanner to that location. Tracking capability included.
*/

#include <stdio.h>
#include <ic.h>
#include <string.h>

/*
   for 4/280 replace ic200.h with ic.h
#include <ic200.h>
*/

/* INITIALIZE FUNCTIONS      */

void scanner();
int cotran(), cotranbs(), itoa(), reverse();
FILE *fp;

main(argc,argv)    /* START MAIN */
int argc ;
char *argv[] ;
{
    struct fsptr *fb ;
    int i, j, startx, starty, totalx, totaly;
    int fx, fy, xsize, ysize, oldx, oldy;

    fp = fopen ("/dev/ttyh1", "w");    /* write mode */

    if(argc > 1) fb = openfs(argv[1]);

    else {    /* bark and die */
        fprintf(stderr, "Usage: scanaq fb [xsearch ysearch]\n") ;
        exit(1);
    }

    if(argc > 3 ){
        xsize = atoi(argv[2]) ;
        ysize = atoi(argv[3]) ;
    } else {
        xsize = 200 ;
        ysize = 200 ;
    }
}

```

```

start_over:
/*  printf("First search\n") ; */

    acquire_fb(fb) ; /* sample first frame */

/*
* If nothing found continue acquiring and testing full field
*/

    while( scan_fb( fb,                /* fsptr */
        0, 0,                          /* startx, starty */
        fb->xsize, fb->ysize,           /* totalx, totaly */
        &fx, &fy /* pointers to fx, fy - returns position of object */
    ))
        acquire_fb(fb) ; /* get another frame */

/*
* found an object - tell the scanner!
*/

    scanner(fx,fy);

/*  Make a 200-square pixel box around the target location */

    startx = fx - xsize/2 ;
    starty = fy - ysize/2 ;
    totalx = xsize ;
    totaly = ysize ;

/*
* clip search box in fb
*/
    startx = (fx - xsize/2 > 0) ? fx - xsize/2 : 0 ;
    starty = (fy - ysize/2 > 0) ? fy - ysize/2 : 0 ;

    if(startx + xsize > fb->xsize) totalx = fb->xsize - startx ;
    if(starty + ysize > fb->ysize) totaly = fb->ysize - starty ;

/*
* Tracking loop
*/

    while(1){
        oldx = fx;
        oldy = fy;

        acquire_fb(fb) ;
        if(scan_fb(fb, startx, starty, totalx, totaly, &fx, &fy ))
            goto start_over ;
    }

```

```

/*      printf(" %d %d \n", fx, fy ) ; */
      if ((abs(oldx - fx) > 1) || (abs(oldy - fy) > 1)) scanner(fx,fy);

      startx = (fx - xsize/2 > 0) ? fx - xsize/2 : 0 ;
      starty = (fy - ysize/2 > 0) ? fy - ysize/2 : 0 ;
      totalx = ( startx + xsize > fb->xsize) ? fb->xsize - startx : xsize ;
      totaly = ( starty + ysize > fb->ysize) ? fb->ysize - starty : ysize ;
    }

```

```

}

```

```

#ifdef PTI_VME_MULTIBUS

```

```

short  hp2 = 0x400 ,
        csr = 0x1 ,
        pcra = 0x500 ,
        wpr0 = 0x100,
        upr0 = 0xfeff,
        wpr1 = 0x1000,
        upr1 = 0xefff ;

```

```

#else

```

```

short  hp2 = 0x4 ,
        csr = 0x100 ,
        pcra = 0x5 ,
        wpr0 = 0x1,
        upr0 = 0xfffe,
        wpr1 = 0x10,
        upr1 = 0xffef ;

```

```

#endif

```

```

acquire_fb(fbp)

```

```

struct fsptr *fbp ;

```

```

{
    register i ;
    char fs2_input, zoom ;
    int control;
    struct mvregs *mvr ;

```

```

if(fbp->attr == IC_MIN_VIDEO){
    mvr = (struct mvregs *)fbp->r_addr ;

    zoom = mvr->vtr ;
    mvr->vtr |= VR ;           /* disable zoom */

    if(fbp->fs == 2){          /* if frame buffer 2 */

        fs2_input = mvr->vicr ;
        mvr->vicr &= ~SMI ;
        mvr->vp2 = 0 ;
        mvr->hp2 = hp2 ;
        while(!(mvr->sr & Vb )) ; /* wait for vertical blank */
        mvr->acr = (AQRS|SS0) ; /* start acquire on next field fs2 */
        while(!(mvr->sr & AFS)) ; /* wait for acquire flag high */
        mvr->acr &= 0 ;           /* stop acquire */
        while(mvr->sr & BFS ) ; /* wait for busy flag low */
        mvr->vicr = fs2_input ;
        mvr->hp2 = 0 ;

    } else {                  /* frame buffer 0 or 1 ? */

        control = mvr->csr ;

        mvr->csr = csr ;       /* pcra always */
        mvr->pcra = pcra ;     /* alu or op */
        mvr->vp01 = 0 ;
        mvr->hp01 = 0 ;

        switch(fbp->fs){
            case 0:            /* frame buffer 0 */
                mvr->wpr |= wpr1 ; /* write protect fs1 */
                while(!(mvr->sr & Vb )) ; /* wait for vertical blank */
                mvr->acr = (AQRD|SD0) ; /*start acquire on next field */
                while(!(mvr->sr & AFD)) ; /*wait for acquire flag high*/
                mvr->acr = 0 ;       /* stop acquire */
                while(mvr->sr & BFD ) ; /* wait for busy flag low */
                mvr->wpr &= upr1 ; /* write protect fs1 off */
                break ;
            case 1:            /* frame buffer 1 */
                mvr->wpr |= wpr0 ; /* write protect fs0 */
                while(!(mvr->sr & Vb )) ; /* wait for vertical blank */
                mvr->acr = (AQRD|SD0) ; /*start acquire on next field*/
                while(!(mvr->sr & AFD)) ; /*wait for acquire flag high*/
                mvr->acr = 0 ;       /* stop acquire */
                while(mvr->sr & BFD ) ; /* wait for busy flag low */
                mvr->wpr &= upr0 ; /* write protect fs0 off */
                break ;
            default:
                fprintf(stderr,
                    "acquire_fb: illegal argument %s\n", fbp->name);
        }
    }
}

```

```

        }
        mvr->csr = control;
    }
    mvr->vtr = zoom ;
}

}

/*
 *scan_fb    returns 0 if pixel found, 1 if no pixel found above threshold
 */

scan_fb(fbp, startx, starty, totalx, totaly, x, y )
struct fbp *fbp ;
int startx, starty, totalx, totaly ;
int *x, *y ;
{
    register unsigned char *pix_addr ;
    register unsigned short *sh_addr ;
    register int i, j ,
        sx = startx, sy = starty,
        tx = startx + totalx, ty = starty + totaly ;

    if (sy == 0) sy = 1 ;
    if (sx == 0) sx = 1 ;
    if (ty >= 512) ty = 512 - sy ;

    for(i=sy; i < ty ; i++){
        pix_addr = (unsigned char *) ( fbp->addr + i * fbp->bsize + startx ) ;
        sh_addr = (unsigned short *) ((int)pix_addr & 0xffffffe) ;
        for(j = sx ; j < tx ; j += 2) {
            if(*sh_addr++){
                *x = j ;
                *y = i ;
                return 0 ;
            }
        }
    }
    return 1 ;
}

/* END SCAN_FB */

/* SCANNER - transforms x,y's to scanner coordinates and passes them to
 * the laser scanner through the serial port.
 */

void scanner(x,y)
int x,y;
{
    /* Declare CCD Camera Constants */

```

```
float ary=6.6, arx=8.8, f=12.5, npy=485., npx=512.;
```

```
/* Declarations */
```

```
int xsc, ysc;
char xstr[6], ystr[6];
```

```
/* Coordinate Transformation */
```

```
xsc = cotranbs ((float)x, npx, arx, f);
ysc = cotran ((float)y, npy, ary, f);
```

```
/* Integer to a String Conversion of Scanner Coordinates */
```

```
itoa (xsc, xstr);
itoa (ysc, ystr);
```

```
/* Print to screen
```

```
printf ("X = %d \nY = %d \n", x, y);
printf ("XSC = %d \nYSC = %d \n", xsc, ysc);
printf ("XSTR = %s \nYSTR = %s \n", xstr, ystr);
```

```
*/
```

```
/* Output through ALM serial port to the laser scanner */
```

```
fprintf (fp, "CL\nBX%s\nBY%s\n", xstr, ystr);
```

```
} /* END MAIN */
```

```
/* Coordinate Transformation from CRT Screen to the Laser Scanner */
```

```
cotran (cc,np,ar,f)
float ar,f,np,cc;
{
float sc;
sc = 32767 * (1 - (2.475 * (cc/np - 0.5) * ar/f)) + 0.5;
return ((int)sc);
} /* END COTRAN*/
```

```
/* Coordinate Transformation from CRT Screen to the Laser Scanner */
```

```
/* WITH MIRROR IMAGE SHIFT DUE TO BEAM SPLITTER BEFORE CCD CAMERA */
```

```
cotranbs (cc,np,ar,f)
float ar,f,np,cc;
{
float sc;
```



```

sc = 32767 * (1 - (2.475 * ((np-cc)/np - 0.5) * ar/f)) + 0.5;
return ((int)sc);
}                                /*      END COTRANBS*/

```

```
/* Integer to a String Conversion Routine */
```

```

itoa ( n, s)
    int n;
    char s[];
{
    int i, sign;

    if ((sign = n) < 0)                /* record sign*/
        n = -n;
    i = 0;
    do {                               /* generate digits in reverse order*/
        s[i++] = n % 10 + '0';         /* get next digit*/
    } while ((n /= 10) > 0);           /* delete it*/
    if (sign < 0)
        s[i++] = '-';
    s[i] = '\0';
    reverse (s);
}                                     /*      END ITOA      */

```

```
/* Reverse String s in Place */
```

```

reverse ( s)
    char s[];
{
    int c, i, j;

    for (i = 0, j = strlen(s)-1; i<j; i++, j--) {
        c = s[i];
        s[i] = s[j];
        s[j] = c;
    }
}                                     /*      END REVERSE*/

```

```

/* temp.c */
/*
                                June 18, 1990
                                S. Hiser & D. Benson
*/
/* Program to scan the FOV of a CCD camera, find the location of a target (after thresholding), and
   direct the laser scanner to that location. Tracking capability included. Clocking capability included.
*/

#include <stdio.h>
#include <ic.h>
#include <string.h>
#include <sys/time.h>

/*
   for 4/280 replace ic200.h with ic.h
#include <ic200.h>
*/

/* INITIALIZE FUNCTIONS */

void scanner();
int cotran(), cotranbs(), itoa(), reverse();
FILE *fp;

int    rv;
struct timeval    tv1, tv2, *tp1, *tp2;
struct timezone    *tzp;
long    delta;

main(argc,argv)    /* START MAIN */
int argc ;
char *argv[] ;
{
    struct fsptr *fb ;
    int i, j, startx, starty, totalx, totaly ;
    int fx, fy, xsize, ysize, oldx, oldy;

    tp1 = &tv1;
    tp2 = &tv2;
    tzp = 0;
    tv1.tv_sec = tv2.tv_sec = 0;
    tv1.tv_usec = tv2.tv_usec = 0;
    rv = gettimeofday(tp1,tzp);    /* get first time */

    /* fp = fopen ("/dev/ttyh1", "w");    */

    if(argc > 1) fb = openfs(argv[1]);

    else {    /* bark and die */

```

```

    fprintf(stderr, "Usage: scanaq fb [xsearch ysearch]\n") ;
    exit(1);
}

if(argc > 3 ){
    xsize = atoi(argv[2]) ;
    ysize = atoi(argv[3]) ;
} else {
    xsize = 200 ;
    ysize = 200 ;
}

start_over:
/* printf("First search\n") ; */
    acquire_fb(fb) ; /* sample first frame */

/*
 * If nothing found continue acquiring and testing full field
 */

    while( scan_fb( fb,          /* fsptr */
        200, 200,                /* startx, starty */
        100, 100,                /* totalx, totaly */
        &fx, &fy                 /* pointers to fx, fy - returns position of object */
    ) )
        acquire_fb(fb) ;          /* get another frame */

/*
 * found an object - tell the scanner!
 */

    scanner(fx,fy);

/* Make a 200-square pixel box around the target location */

    startx = fx - xsize/2 ;
    starty = fy - ysize/2 ;
    totalx = xsize ;
    totaly = ysize ;

/*
 * clip search box in fb
 */
    startx = (fx - xsize/2 > 0) ? fx - xsize/2 : 0 ;
    starty = (fy - ysize/2 > 0) ? fy - ysize/2 : 0 ;

    if(startx + xsize > fb->xsize) totalx = fb->xsize - startx ;
    if(starty + ysize > fb->ysize) totaly = fb->ysize - starty ;

```

```

/*
 * Tracking loop
 */

while(1){
    oldx = fx;
    oldy = fy;

    acquire_fb(fb) ;
    if(scan_fb(fb, startx, starty, totalx, totaly, &fx, &fy ))
        goto start_over ;

/*    printf(" %d %d \n", fx, fy ) ; */
    if ((abs(oldx - fx) > 1) || (abs(oldy - fy) > 1)) scanner(fx,fy);

    startx = (fx - xsize/2 > 0) ? fx - xsize/2 : 0 ;
    starty = (fy - ysize/2 > 0) ? fy - ysize/2 : 0 ;
    totalx = ( startx + xsize > fb->xsize) ? fb->xsize - startx : xsize ;
    totaly = ( starty + ysize > fb->ysize) ? fb->ysize - starty : ysize ;
}

}

#ifdef PTI_VME_MULTIBUS
short  hp2 = 0x400 ,
        csr = 0x1 ,
        pcra = 0x500 ,
        wpr0 = 0x100,
        upr0 = 0xfeff,
        wpr1 = 0x1000,
        upr1 = 0xffff ;
#else
short  hp2 = 0x4 ,
        csr = 0x100 ,
        pcra = 0x5 ,
        wpr0 = 0x1,
        upr0 = 0xfffe,
        wpr1 = 0x10,
        upr1 = 0xffef ;
#endif

acquire_fb(fbp)
struct fsptr *fbp ;
{
    register i ;
    char fs2_input, zoom ;
    int control;
    struct mvregs *mvr ;

```

```

if(fbp->attr == IC_MIN_VIDEO){
    mvr = (struct mvregs *)fbp->r_addr ;

    zoom = mvr->vtr ;
    mvr->vtr |= VR ;          /* disable zoom */

    if(fbp->fs == 2){          /* if frame buffer 2 */

        fs2_input = mvr->vicr ;
        mvr->vicr &= ~SMI ;
        mvr->vp2 = 0 ;
        mvr->hp2 = hp2 ;
        while(!(mvr->sr & Vb )) ; /* wait for vertical blank */
        mvr->acr = (AQRS|SS0) ; /* start acquire on next field fs2 */
        while(!(mvr->sr & AFS)) ; /* wait for acquire flag high */
        mvr->acr &= 0 ;          /* stop acquire */
        while(mvr->sr & BFS ) ; /* wait for busy flag low */
        mvr->vicr = fs2_input ;
        mvr->hp2 = 0 ;

    } else {                  /* frame buffer 0 or 1 ? */

        control = mvr->csr ;

        mvr->csr = csr ;          /* pcra always */
        mvr->pcra = pcra ;        /* alu or op */
        mvr->vp01 = 0 ;
        mvr->hp01 = 0 ;

        switch(fbp->fs){
            case 0:             /* frame buffer 0 */
                mvr->wpr |= wpr1 ; /* write protect fs1 */
                while(!(mvr->sr & Vb )) ; /* wait for vertical blank */
                mvr->acr = (AQRD|SD0) ; /*start acquire on next field */
                while(!(mvr->sr & AFD)); /*wait for acquire flag high*/
                mvr->acr = 0 ;          /* stop acquire */
                while(mvr->sr & BFD ) ; /* wait for busy flag low */
                mvr->wpr &= upr1 ; /* write protect fs1 off */
                break ;
            case 1:             /* frame buffer 1 */
                mvr->wpr |= wpr0 ; /* write protect fs0 */
                while(!(mvr->sr & Vb )) ; /* wait for vertical blank */
                mvr->acr = (AQRD|SD0) ; /*start acquire on next field*/
                while(!(mvr->sr & AFD)); /*wait for acquire flag high*/
                mvr->acr = 0 ;          /* stop acquire */
                while(mvr->sr & BFD ) ; /* wait for busy flag low */
                mvr->wpr &= upr0 ; /* write protect fs0 off */
                break ;
            default:
                fprintf(stderr,
                    "acquire_fb: illegal argument %s\n",fbp->name);
        }
    }
}

```

```

        }
        mvr->csr = control;
    }
    mvr->vtr = zoom ;
}

}

/*
*scan_fb    returns 0 if pixel found, 1 if no pixel found above threshold
*/

scan_fb(fbp, startx, starty, totalx, totaly, x, y )
struct fsptr *fbp ;
int startx, starty, totalx, totaly ;
int *x, *y ;
{
    register unsigned char *pix_addr ;
    register unsigned short *sh_addr ;
    register int i, j ,
        sx = startx, sy = starty,
        tx = startx + totalx, ty = starty + totaly ;

    if (sy == 0) sy = 1 ;
    if (sx == 0) sx = 1 ;
    if (ty >= 512) ty = 512 - sy ;

    for(i=sy; i < ty ; i++){
        pix_addr = (unsigned char *) ( fbp->addr + i * fbp->bsize + startx ) ;
        sh_addr = (unsigned short *) ((int)pix_addr & 0xffffffe) ;
        for(j = sx ; j < tx ; j += 2) {
            if(*sh_addr++){
                *x = j ;
                *y = i ;
                return 0 ;
            }
        }
    }
    return 1 ;
}

/* END SCAN_FB */

/* SCANNER - transforms x,y's to scanner coordinates and passes them to
 * the laser scanner through the serial port.
*/

void scanner(x,y)
int x,y;
{

```

```

/* Declare CCD Camera Constants      */

    float ary=6.6, arx=8.8, f=12.5, npy=485., npx=512.;

/* Declarations      */

    int xsc, ysc;
    char xstr[6], ystr[6];

/* Coordinate Transformation      */

    xsc = cotranbs ((float)x,npx,arx,f);
    ysc = cotran ((float)y,npy,ary,f);

/* Integer to a String Conversion of Scanner Coordinates */

    itoa (xsc, xstr);
    itoa (ysc, ystr);

rv = gettimeofday(tp2,tzp); /* get second time */
delta = 1000*(tv2.tv_sec - tv1.tv_sec) + (tv2.tv_usec - tv1.tv_usec)/1000;
printf("Elapsed time = %d milliseconds\n", delta);
exit(0);

/* Print to screen

printf ("X = %d \nY = %d \n", x, y);
printf ("XSC = %d \nYSC = %d \n", xsc, ysc);
printf ("XSTR = %s \nYSTR = %s \n", xstr, ystr);

*/

/* Output through ALM serial port to the laser scanner */

/* fprintf (fp, "CL\nBX%s\nBY%s\n", xstr, ystr); */

}          /*      END MAIN      */

/* Coordinate Transformation from CRT Screen to the Laser Scanner */

cotran (cc,np,ar,f)
float ar,f,np,cc;
{
    float sc;
    sc = 32767 * (1 - (2.475 * (cc/np - 0.5) * ar/f)) + 0.5;
    return ((int)sc);
}          /* END COTRAN*/

```

```
/* Coordinate Transformation from CRT Screen to the Laser Scanner */
/* WITH MIRROR IMAGE SHIFT DUE TO BEAM SPLITTER BEFORE CCD CAMERA */
```

```
cotranbs (cc,np,ar,f)
float ar,f,np,cc;
{
float sc;
sc = 32767 * (1 - (2.475 * ((np-cc)/np - 0.5) * ar/f)) + 0.5;
return ((int)sc);
}                                /*      END COTRANBS*/
```

```
/* Integer to a String Conversion Routine */
```

```
itoa ( n, s)
int n;
char s[];
{
int i, sign;

if ((sign = n) < 0)                /* record sign*/
    n = -n;
i = 0;
do {                                /*      generate digits in reverse order*/
    s[i++] = n % 10 + '0';          /* get next digit*/
} while ((n /= 10) > 0);           /* delete it*/
if (sign < 0)
    s[i++] = '-';
s[i] = '\0';
reverse (s);
}                                /*      END ITOA      */
```

```
/* Reverse String s in Place */
```

```
reverse ( s)

char s[];
{
int c, i, j;

for (i = 0, j = strlen(s)-1; i < j; i++, j--) {
    c = s[i];
    s[i] = s[j];
    s[j] = c;
}
}                                /*      END REVERSE*/
```



## Appendix E

### PARAMETERS FOR OUTDOOR EXPERIMENTS

Plans have been developed to track 12-gauge shotgun slugs over the Chesapeake Bay using a 5 W argon-ion laser and a CCD camera for acquisition. The initial concern was whether the CCD camera could see the slug. The power returned  $P_{ret}$  to the CCD is given by

$$P_{ret} = P_{out} S A_{det} \left[ \frac{A_{slug}}{A_{beamR}} \right], \quad (E1)$$

where  $P_{out}$  is 5 W argon-ion power (multiline),  $S$  is  $2 \times 10^{-3}/\text{cm}^2$  local reflectivity measured experimentally from a slug with retrotape across its back,  $A_{det}$  is the aperture area of the CCD camera lens,  $A_{slug}$  is the area of the back of the slug, and  $A_{beamR}$  is the area of the argon-ion beam at range  $R$ . Equation (E1) straightforwardly reduces to

$$P_{ret} = P_{out} S A_{det} \left[ \frac{d_{slug}}{\theta R} \right]^2, \quad (E2)$$

where

$$A_{det} = \frac{\pi}{4} \left[ \frac{f_l}{F} \right]^2 \quad (E3)$$

and  $f_l$  is 85 mm, the focal length of the CCD camera lens,  $F$  is 5.6 (i.e., the F-stop setting of that lens),  $d_{slug}$  is 1.75 cm (i.e., the slug diameter),  $\theta$  is the divergence of the outgoing laser beam, and  $R$  is the range to the slug. Acquisition has been planned to begin at  $R = 30$  m. The corresponding return powers for various divergence angles are listed in Table E1. Slugs could be consistently fired into a 15 cm to 30 cm beam at a range of 30 m. Comparing the return powers of Table E1 to the CCD minimum illumination of  $< 0.1 \mu\text{W}$ , the slug should be visible with the CCD camera.

Table E1 — Expected Return Power from a Retrotaped Slug at 30 m Range for Various Argon-ion Beam Divergences

Laser beam divergence $\theta$ (mrad)	Expected power returned $P_{ret}$ ( $\mu\text{W}$ )
5.0	245
7.5	109
10.0	61

The next question for the slug experiment is "How well can the Digicon see the slug once the target has been located?" The Digicon's sensitivity is  $N_o = 30$  photons/pulse/pixel or  $E_o = N_o h c / \lambda = 1.12 \times 10^{-17}$  J/pulse/pixel. The energy returned / pulse  $E_{ret}$  to the Digicon is given by

$$E_{ret} = E_{out} \gamma_1 \gamma_2 S A_{det} \left( \frac{A_{slug}}{A_{beam_R}} \right) \quad (E4)$$

or

$$E_{ret} = E_{out} \gamma_1 \gamma_2 S A_{det} \left( \frac{d_{slug}}{\theta R} \right)^2 \quad (E5)$$

where  $E_{out}$  is 0.19 J/pulse (i.e., the laser output energy),  $\gamma_1$  is 0.87 (i.e., the transmitter optical transmission),  $\gamma_2$  is 0.45 (i.e., the receiver optical transmission),  $S$  is  $2 \times 10^{-3}/\text{cm}^2$  (i.e., local reflectivity),  $A_{det}$  is  $0.94 \text{ cm}^2$  with  $f_i = 350 \text{ mm}$  and  $F = 32$ ,  $d_{slug}$  is 1.75 cm (i.e., the slug diameter),  $\theta$  is the outgoing beam divergence, and  $R$  is the range to the slug. Assuming a doubled Nd-Yag beam divergence of 10 mrad and 190 mJ/pulse ( $5 \times 10^{17}$  photons/pulse) out of the laser, the Digicon could detect a slug out to a range of 6 km. At a 35 m range,  $E_{ret}/E_o = 10^{10}$ . Thus, the Digicon can detect the slug very easily. (In fact, neutral density filters and beam splitters would be required to protect the Digicon from saturation and for eye safety reasons.) The key to the slug experiment is the speed of the acquisition and handoff. We have estimated seeing 5 or 6 successive images of the slug before it falls out of the FOR.

For the extended targets, i.e., boats in the water, a 10 mrad divergence of the Nd-Yag beam would again be suitable. Ranges of 0.4 km to 2 km for boats in the bay would be possible. If necessary, retortape could be used every few feet along the boat's length. Varying range returns would be observed on the  $8 \times 8$  range-per-pixel image as a boat turned in the water.

## Appendix F

### LASER SAFETY ANALYSIS

#### F1. LASER CHARACTERISTICS

##### F1.1 Pulsed, Doubled Nd: YAG Laser (532 nm)

###### *F1.1.1 Physical Description*

180 mJ/pulse  
0.6 mrad divergence  
10 ns pulse length ( $t$ )  
30 Hz pulse repetition frequency (PRF)  
0.25 s ocular exposure time ( $T$ )\*  
10.0 s skin exposure time ( $T$ )  
6 mm pulse diameter  
0.64 J/cm<sup>2</sup> radiant exposure ( $H$ )†  
2.5 W/cm<sup>2</sup> average irradiance ( $E$ )†

###### *F1.1.2 Ocular Exposure for Intrabeam Viewing*

The maximum permissible exposure (MPE) to a low repetition (1 kHz), pulsed laser is determined by the most stringent of the following exposure requirements.

###### **MPE per Pulse Corrected for PRF**

The MPE to a single pulse from the laser described above is given in Table 5 of Ref. F1 as

$$MPE = 1.8t^{3/4} \times 10^{-3} J/cm^2. \quad (F1)$$

For a pulse duration of 10 ns,

$$MPE = 5.0 \times 10^{-7} J/cm^2. \quad (F2)$$

---

\*Eye movement through the natural aversion response to visible light defines the exposure time to the laser.

†Assuming the worst case of no atmosphere attenuation.

Using the PRF correction factor of  $n^{-1/4}$ , where

$$n = \text{prf} \cdot T \quad (\text{F3})$$

yields

$$MPE_{\text{pulse}} = n^{-1/4} \cdot MPE = 3.0 \times 10^{-7} \text{ J/cm}^2. \quad \ddagger \quad (\text{F4})$$

### Cumulative Exposure to a Train of Pulses

The cumulative exposure to a train of laser pulses is

$$MPE_{\text{cum}} = T \cdot \text{prf} \cdot MPE/\text{pulse} = 2.3 \times 10^{-6} \text{ J/cm}^2, \quad (\text{F5})$$

or an average irradiance of

$$E = MPE_{\text{cum}}/T = 9.1 \times 10^{-6} \text{ W/cm}^2. \quad (\text{F6})$$

### Total Exposure to a Train of Pulses

Since exposure times are limited with visible radiation ( $n \cdot t$  exposure  $< 10$  s), cumulative exposure to the entire train of pulses is not a limiting consideration here.

The more stringent requirement in calculation 1 yields the following safety glass optical density (OD) for safe laser viewing at the source:

$$OD = \log \left[ \frac{H}{MPE_{\text{pulse}}} \right] = 7. \quad (\text{F7})$$

Standard doubled Nd:YAG glasses (i.e., Glendale Series B) provide adequate protection.

### F1.1.3 Skin Exposure

The maximum permissible skin exposure to a pulsed, visible laser is given in Table 7 of Ref. F1 as

$$MPE_{\text{pulse}} = 0.02 \text{ J/cm}^2. \quad (\text{F8})$$

Correcting for the PRF of the laser yields

$$MPE_{\text{pulse}} = n^{-1/4} \cdot MPE = 4.8 \times 10^{-3} \text{ J/cm}^2. \quad \ddagger \quad (\text{F9})$$

The cumulative exposure is

$$MPE_{\text{cum}} = T \cdot \text{prf} \cdot MPE/\text{pulse} = 1.4 \text{ J/cm}^2. \quad (\text{F10})$$

The limiting skin exposure as determined by correcting for the PRF is exceeded by the radiant exposure at the laser source by 1.3 orders of magnitude.

---

$\ddagger$ Indicates a limiting value.

**F1.2 Continuous Wave Argon Ion Laser (514.5 nm)*****F1.2.1 Physical Description***

5 W  
 0.7 mrad divergence  
 0.25 ocular exposure time\* ( $t$ ,  $T$ )  
 10.0 s skin exposure time ( $T$ )  
 0.7 cm pulse diameter  
 17.6 W/cm<sup>2</sup> average irradiance ( $E$ )†

***F1.2.2 Ocular Exposure for Intrabeam Viewing***

The MPE to a continuous-wave, visible laser is given in Table 5 of Ref. F1 as

$$MPE = 1.8t^{3/4} \times 10^{-3} J/cm^2. \quad (F11)$$

For an exposure time of 0.25 s,

$$MPE = 6.4 \times 10^{-4} J/cm^2. \quad \ddagger \quad (F12)$$

This yields the following OD requirement for eyesafe laser viewing at the laser source:

$$OD = \log[H/MPE] = 3 \quad (H = E \cdot T). \quad (F13)$$

Standard Argon Ion glasses (i.e., Glendale Argon Ion) provide adequate protection for safe viewing.

***F1.2.3 Skin Exposure***

The maximum permissible skin exposure to a continuous-wave, visible laser is given in Table 7 of Ref. F1 as

$$MPE_{skin} = 0.2 W/cm^2 = 2.0 J/cm^2 \quad \ddagger \quad (F14)$$

for an exposure time ( $T$ ) of 10 s. Using

$$H = E \cdot T = 176 J/cm^2, \quad (F15)$$

the radiant exposure exceeds the allowable limit by two orders of magnitude at the laser source.

**F2. SAFETY CALCULATION RESULTS AND PROCEDURES****F2.1 Case A: 1.25 cm Doubled Nd:YAG Laser Beam on the Target Board at 15 m Distance**

Radiant exposure - 0.14 J/cm<sup>2</sup>

---

\*Eye movement through the natural aversion response to visible light defines the exposure time to the laser.

†Assuming the worst case of no atmospheric attenuation.

‡Indicates a limiting value.

MPE - Comparing the MPEs from Section F1 to the radiant exposure in this experiment yields the following:

Ocular:  $OD_{safe} = 6$  (Standard Glendale Series B doubled Nd:YAG safety glasses).

Skin:  $20 \times$  excess for skin exposure of 10 s exposure. The laser is not safe under these conditions.

Nominal Hazard Zone (NHZ) - The entire building will be considered a hazard zone. A barrier will be constructed to block the end of the light tunnel and movable barriers will be available to block work areas in B250 (see Fig. F1(a)). Flashing red lights must be on when laser is in operation. Doors must be locked when laser is running. Black cloth will be installed on any obstructions in the light tunnel to avoid any stray specular reflections.

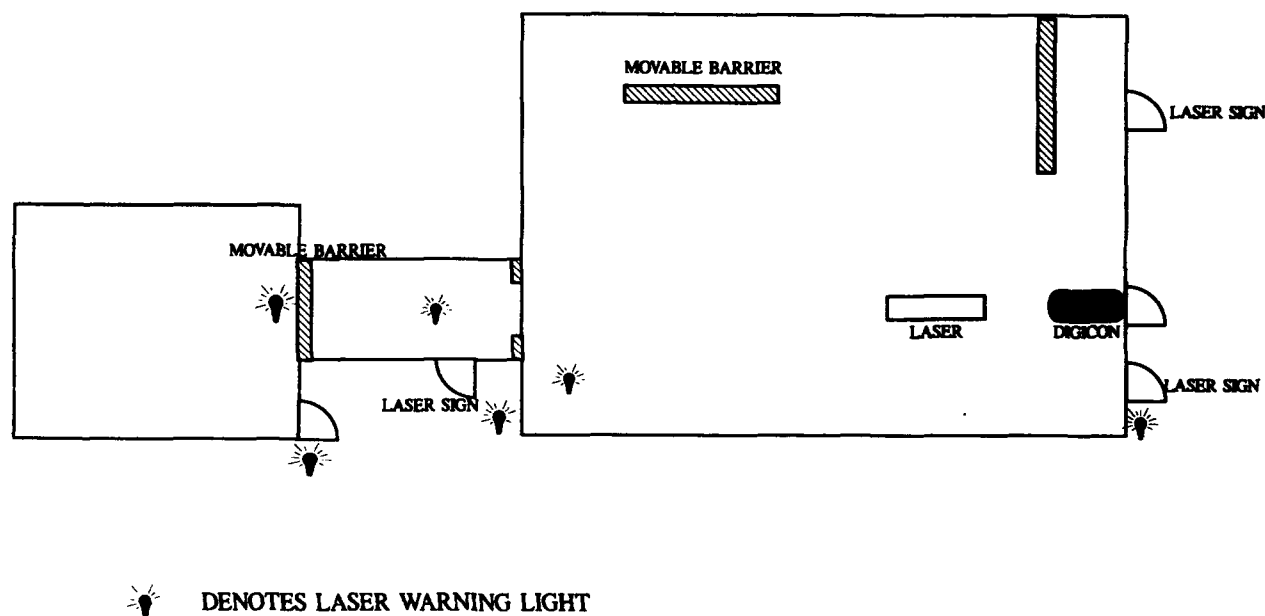


Fig. F1(a) — Interior of Building 250 with warning lights and barriers indicated

Diffuse Reflections - The maximum radiant exposure on a diffuse surface that will produce hazardous reflections is  $20 \text{ J/cm}^2$  for an exposure time of 0.25 s [F1, Table 3].

Extended Source - The extended source limitation is not valid since the beam will not produce diffuse reflections that will constitute an eye hazard.

Standard Operating Procedure - See the attached procedure 1 (Section F4).

**F2.2 Case B: 1.25 m Doubled Nd:YAG Laser Beam on Target Board at 16 m Distance (1.75 m Diameter)**

Radiant Exposure -  $7.9 \times 10^6 \text{ J/cm}^2$

MPE - Comparing the MPEs from Section F1 to the radiant exposure in this experiment yields the following:

Ocular:  $OD_{safe} = 2$  (Standard Glendale Series B doubled Nd:YAG safety glasses).

**Skin:** 2 orders of magnitude below exposure threshold for a 10 s exposure.

**Nominal Hazard Zones -** See Case A above.

**Diffuse Reflections -** The maximum radiant exposure on a diffuse surface that will produce hazardous reflections is  $20 \text{ J/cm}^2$  for an exposure time of 0.25 s [F1, Table 3].

**Extended Source -** The extended source limitation is not valid since the beam will not produce diffuse reflections that will constitute an eye hazard.

**Standard Operating Procedure -** See the attached procedure 1 (Section F4).

**F2.3 Case C: Doubled Nd:YAG Laser Beam on Targets Along Light Tunnel (Extremes: 20 cm at 61 m, 5 cm at 15 m)**

**Radiant Exposure -**  $8.9 \times 10^{-3} \text{ J/cm}^2$  at the entrance of the tunnel (worst case).

**MPE -** Comparing the MPEs from Section F1 to the radiant exposure in this experiment yields the following:

**Ocular:**  $\text{OD}_{\text{safe}} = 5$  (Standard Glendale Series B doubled Nd:YAG safety glasses).

**Skin:** A factor of 5 above the threshold exposure for a 10 s exposure. The laser is not safe under these conditions.

**NHZ -** See Case A above.

**Diffuse Reflections -** The maximum radiant exposure on a diffuse surface that will produce hazardous reflections is  $20 \text{ J/cm}^2$  for an exposure time of 0.25 s [F1, Table 3].

**Extended Source -** The extended source limitation is not valid since the beam will not produce diffuse reflections that will constitute an eye hazard.

**Standard Operating Procedure -** See the attached procedure 1 (Section F4).

**F2.4 Case D: Targeting Beam with Argon Ion Laser for Slug**

**F2.4.1 15 cm Diameter Beam at 31 m Distance (Worst Case for Laser Safety)**

**Radiant Exposure -**  $0.11 \text{ J/cm}^2$

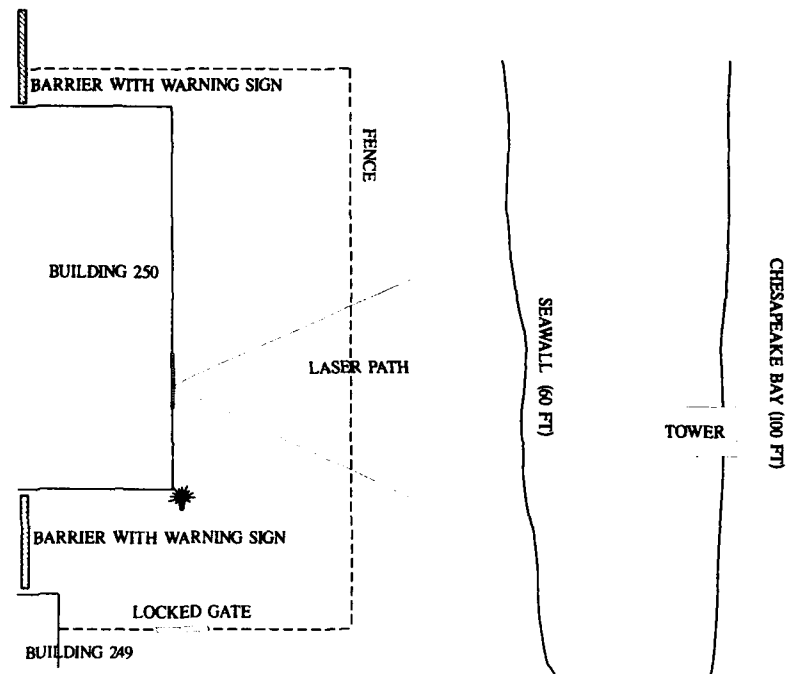
**MPE -** See the values listed in Section F1 for the Argon Ion laser MPEs. Comparing the MPEs to the radiant exposure in this experiment yields the following:

**Ocular:**  $\text{OD}_{\text{safe}} = 3$ . In near-field viewing, the same safety considerations should be applied as those at the laser source. Standard Glendale Argon Ion safety glasses will be used.

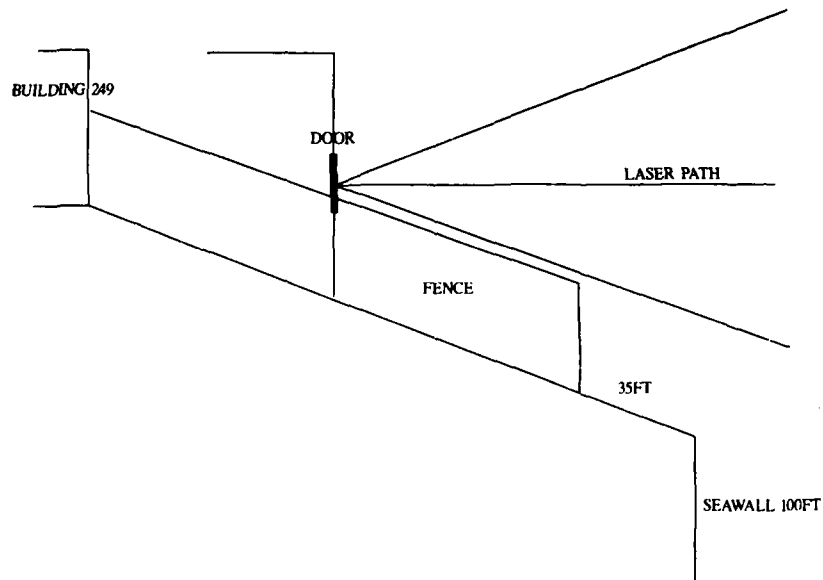
In far-field viewing such as in or over the water, no transient personnel are expected. All traffic must be excluded from the NHZ detailed below. Any control personnel in the area should wear the eye protection specified above.

Skin: 2.5 orders of magnitude below the exposure threshold for 10 s exposure.

NHZ - See Figs. F1(b) and F2. Barriers will be placed to deny access to the hazard zones behind CBD, Building 250. Red lights will be in operation outside the building and danger signs in place when the laser is firing. Test control and the NRL boat will control traffic in the NHZ as required. All safety procedures cited in A (SOP 1) will be used in Building 250. All range control procedures described in SOP 2 (see Section F5) will be used.



(top view)



(side view)

Fig. F1(b) — Exterior of Building 250 with warning lights and barriers indicated



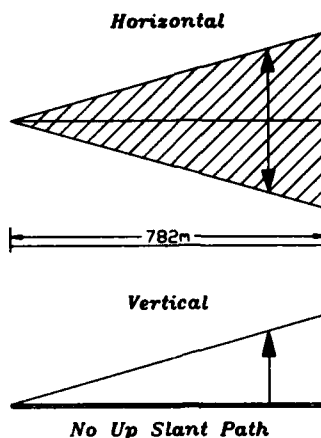


Fig. F2 — NHZ for Case D, 15 cm diameter beam

**Nominal Ocular Hazard Distance (NOHD)** - The NOHD, assuming a worst case of no atmospheric attenuation, is given by

$$r = \frac{1}{\phi} \left[ \sqrt{\frac{1.27\Phi}{MPE}} - a \right] = 782m. \quad (F16)$$

Here,  $r$  is distance,  $\phi$  is divergence,  $\Phi$  is total energy, and  $a$  is the original beam radius. For this lens,  $\Phi$  is  $2.5 \times 10^{-3}$  rad.

**Diffuse Reflections** - The maximum radiant exposure on a diffuse surface that will produce hazardous reflections from an Argon laser is  $20 \text{ J/cm}^2$  for an exposure time of  $0.25 \text{ s}$  [F1, Table 3]. Reflections from the fence or the water tower will not produce reflections that are hazardous outside of the NHZ. Glossy foliage, raindrops, and other objects are not hazardous targets [F2].

**Water Reflections** - Specular reflections from standing water do not present a significant additional hazard to personnel outside the NHZ [F2].

**Retro Return** - The retro return will be less than 0.5% of the radiant intensity from the output laser beam. This exposure does constitute a safety hazard. This return will be directed at the laser operator; safety glasses will be used and no additional safety hazard is incurred.

**Extended Source** - The extended source limitation is not valid since the beam will not produce diffuse reflections that will constitute an eye hazard.

**Standard Operating Procedure** - See the attached procedure 2 (Section F5).

#### **F2.4.2 30 cm Diameter Beam at 31 m Distance**

**Radiant Exposure** -  $2.8 \times 10^{-2} \text{ J/cm}^2$

**MPE** - See the values listed in Section F1 for the Argon Ion laser MPEs. Comparing the MPEs to the radiant exposure in this experiment yields the following:

**Ocular:**  $OD_{safe} = 2$ . In near-field viewing, the same safety considerations should be applied as those at the laser source. Standard Glendale Argon Ion safety glasses will be used.

In far-field viewing such as in or over the water, no transient personnel are expected. All traffic must be excluded from the NHZ detailed below. Any control personnel in the area should wear the eye protection specified above.

**Skin:** 1 order of magnitude below the exposure threshold for 10 s exposure.

**NHZ** - See Figs. F1(b) and F3. Barriers will be placed to deny access to the hazard zones behind CBD, Building 250. Red lights will be in operation outside the building and danger signs in place when the laser is firing. Test control and the NRL boat will control traffic in the NHZ as required. All safety procedures cited in A (SOP 1) will be used in Building 250. All range control procedures described in SOP 2 will be used.

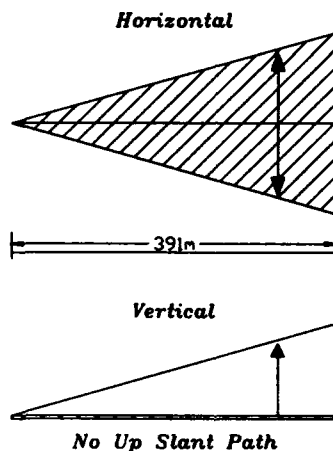


Fig. F3 — NHZ for Case D, 30 cm diameter beam

**NOHD** - The NOHD is 391 m assuming a worst case of no atmospheric attenuation. For this lens,  $\phi$  is  $5.0 \times 10^{-3}$  rad.

**Diffuse Reflections** - The maximum radiant exposure that will produce hazardous reflections from an Argon laser is  $20 \text{ J/cm}^2$  for an exposure of 0.25 s [F1, Table 3]. Reflections from the fence or the water tower will not produce reflections that are hazardous outside of the NHZ. Glossy foliage, raindrops, and other objects are not hazardous targets [F2].

**Water Reflections** - Specular reflections from standing water do not present a significant additional hazard to personnel outside the NHZ [F2].

**Retro Return** - The retro return will be less than 0.5% of the radiant intensity from the output laser beam. This exposure does constitute a safety hazard. This return will be directed at the laser operator; safety glasses will be used and no additional safety hazard is incurred.

**Extended Source** - The extended source limitation is not valid since the beam will not produce diffuse reflections that will constitute an eye hazard.

**Standard Operating Procedure** - See the attached procedure 2 (Section F5).

## **F2.5 Case E: Targeting Beam with Doubled Nd:YAG Laser for Slug**

### ***F2.5.1 15 cm Diameter Beam at 31 m Distance (Worst Case for Laser Safety)***

**Radiant Exposure** -  $9.9 \times 10^{-2} \text{ J/cm}^2$

**MPE** - See the values listed in Section F1 for the Nd:YAG laser MPEs. Comparing the MPEs to the radiant exposure in this experiment yields the following:

**Ocular:**  $OD_{\text{safe}} = 4$ . In near-field viewing, the same safety considerations should be applied as those at the laser source. Standard Glendale Nd:YAG safety glasses will be used.

In far-field viewing such as in or over the water, no transient personnel are expected. All traffic must be excluded from the NHZ detailed below. Any control personnel in the area should wear the eye protection specified above.

**Skin:** 1 order of magnitude below the exposure threshold for 10 s exposure.

**NHZ** - See Figs. F1(b) and F4. Barriers will be placed to deny access to the hazard zones behind CBD, Building 250. Red lights will be in operation outside the building and danger signs in place when the laser is firing. Test control and the NRL boat will control traffic in the NHZ as required. All safety procedures cited in A (SOP 1) will be used in Building 250. All range control procedures described in SOP 2 will be used.

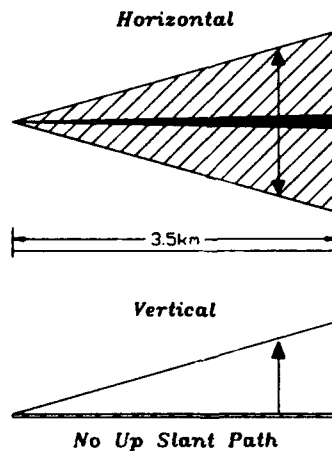


Fig. F4 — NHZ for Case E, 15 cm diameter beam

**NOHD** - The NOHD is 3.5 km assuming a worst case of no atmospheric attenuation. For this lens,  $\phi$  is  $2.5 \times 10^{-3} \text{ rad}$ .

**Diffuse Reflections** - The maximum radiant exposure that will produce hazardous reflections from an Nd:YAG is  $20 \text{ J/cm}^2$  for an exposure of 0.25 s [F1, Table 3]. Reflections from the fence or the water

tower will not produce reflections that are hazardous outside of the NHZ. Glossy foliage, raindrops and other objects are not hazardous targets [F2].

**Water Reflections** - Specular reflections from standing water do not present a significant additional hazard to personnel outside the NHZ [F2].

**Retro Return** - The retro return will be less than 0.5% of the radiant intensity from the output laser beam. This exposure does constitute a safety hazard. This return will be directed at the laser operator; safety glasses will be used and no additional safety hazard is incurred.

**Extended Source** - The extended source limitation is not valid since the beam will not produce diffuse reflections that will constitute an eye hazard.

**Standard Operating Procedure** - See the attached procedure 2 (Section F5).

#### ***F2.5.2 30 cm diameter beam at 31 m distance***

**Radiant Exposure** -  $2.5 \times 10^{-4} \text{ J/cm}^2$

**MPE** - See the values listed in Section F1 for the Nd:YAG laser MPEs. Comparing the MPEs to the radiant exposure in this experiment yields the following:

**Ocular:**  $OD_{\text{safe}} = 3$ . In near-field viewing, the same safety considerations should be applied as those at the laser source. Standard Glendale Nd:YAG safety glasses will be used.

In far-field viewing such as in or over the water, no transient personnel are expected. All traffic must be excluded from the NHZ detailed below. Any control personnel in the area should wear the eye protection specified above.

**Skin:** 1 order of magnitude below the exposure threshold for 10 s exposure.

**NHZ** - See Figs. F1(b) and F5. Barriers will be placed to deny access to the hazard zones behind CBD, Building 250. Red lights will be in operation outside the building and danger signs in place when the laser is firing. Test control and the NRL boat will control traffic in the NHZ as required. All safety procedures cited in A (SOP 1) will be used in Building 250. All range control procedures described in SOP 2 will be used.

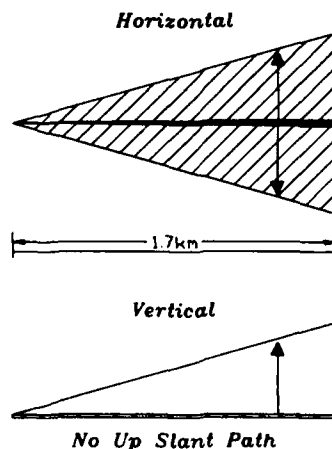


Fig. F5 — NHZ for Case E, 30 cm diameter beam

**NOHD** - The NOHD is 1.7 km assuming a worst case of no atmospheric attenuation. For this lens,  $\phi$  is  $5.0 \times 10^{-3}$  rad.

**Diffuse Reflections** - The maximum radiant exposure that will produce hazardous reflections from an Nd:YAG laser is  $20 \text{ J/cm}^2$  for an exposure of 0.25 s [F1, Table 3]. Reflections from the fence or the water tower will not produce reflections that are hazardous outside of the NHZ. Glossy foliage, raindrops, and other objects are not hazardous targets [F2].

**Water Reflections** - Specular reflections from standing water do not present a significant additional hazard to personnel outside the NHZ [F2].

**Retro Return** - The retro return will be less than 0.5% of the radiant intensity from the output laser beam. This exposure does constitute a safety hazard. This return will be directed at the laser operator; safety glasses will be used and no additional safety hazard is incurred.

**Extended Source** - The extended source limitation is not valid since the beam will not produce diffuse reflections that will constitute an eye hazard.

**Standard Operating Procedure** - See the attached procedure 2 (Section F5).

#### **F2.6 Case F: Targeting Beam with Doubled Nd:YAG Laser to Boat with a 15 m Diameter Beam at 3.1 km Distance (Worst Case for Laser Safety)**

**Radiant Exposure** -  $9.9 \times 10^{-8} \text{ J/cm}^2$

**MPE** - See the values listed in Section F1 for the Nd:YAG laser MPEs. Comparing the MPEs to the radiant exposure in this experiment yields the following:

**Ocular:** Eyesafe by a factor of 3. No safety glasses are needed at the boat for eyesafe viewing. At the laser source, the standard Nd:YAG Glendale safety glasses are required. However, safety glasses may be worn as an added precaution. Any traffic control personnel should wear the eye protection specified above.

**Skin:** 5 orders of magnitude below the exposure threshold for 10 s exposure.

**NHZ** - See Figs. F1(b) and F6. Barriers will be placed to deny access to the hazard zones behind CBD, Building 250. Red lights will be in operation outside the building and danger signs in place when the laser is firing. Test control and the NRL boat will control traffic in the NHZ as required. All safety procedures cited in A (SOP 1) will be used in Building 250. All range control procedures described in SOP 2 will be used.

**NOHD** - The NOHD is 3.1 km assuming a worst case of no atmospheric attenuation. For this lens,  $\phi$  is  $5.0 \times 10^{-3}$  rad.

**Diffuse Reflections** - The maximum radiant exposure that will produce hazardous reflections from Nd:YAG is  $20 \text{ J/cm}^2$  for an exposure of 0.25 s [F1, Table 3]. Reflections from the fence or the water tower will not produce reflections that are hazardous outside of the NHZ. Glossy foliage, raindrops and other objects are not hazardous targets [F2].

**Water Reflections** - For this experiment, the laser will be pointed at an object that is 3.1 km away. The laser is eyesafe at that distance. Therefore, there are no potential hazardous reflections in this experiment.

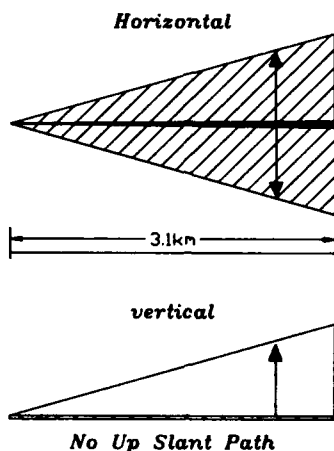


Fig. F6 — NHZ for Case F

**Retro Return** - The retro return will not constitute a safety hazard. In addition, the return will be directed at the laser operator where safety procedures are in place.

**Extended Source** - The extended source limitation is not valid since the beam will not produce diffuse reflections that will constitute an eye hazard.

**Standard Operating Procedure** - See the attached procedure 2 (Section F5).

#### **F2.7 Case G: Targeting Beam with Argon Ion Laser for Clay Target (1 m Diameter Beam at 62 m Distance)**

**Radiant Exposure** -  $3.1 \times 10^{-3} \text{ J/cm}^2$

**MPE** - See the values listed in Section F1 for the Argon Ion laser MPEs. Comparing the MPEs to the radiant exposure in this experiment yields the following:

**Ocular:**  $OD_{\text{safe}} = 1$ . In near-field viewing, the same safety procedures should be applied as at the laser source. Standard Glendale Argon Ion safety glasses will be used.

In the far-field, such as in or over water, no transient personnel are expected. All traffic must be excluded from the NHZ detailed below. Any control personnel in the area should wear the eye protection specified above.

**Skin:** 3 orders of magnitude below the exposure threshold for 10 s exposure.

**NHZ** - See Figs. F1(b) and F7. Barriers will be placed to deny access to the hazard zones behind CBD, Building 250. Red lights will be in operation outside the building and danger signs in place when the laser is firing. Test control and the NRL boat will control traffic in the NHZ as required. All safety procedures cited in A (SOP 1) will be used in Building 250. All range control procedures described in SOP 2 will be used.

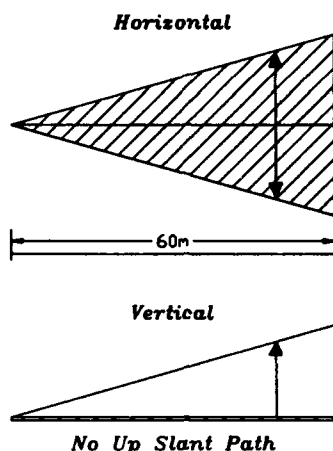


Fig. F7 — NHZ for Case G

**NOHD** - The NOHD is 60 m assuming a worst case of no atmospheric attenuation. For this lens,  $\phi$  is  $7.5 \times 10^{-3}$  rad.

**Diffuse Reflections** - The maximum radiant exposure that will produce hazardous reflections from an Argon laser is  $20 \text{ J/cm}^2$  for an exposure of 0.25 s [F1, Table 3]. Reflections from the fence or the water tower will not produce reflections that are hazardous outside of the NHZ. Glossy foliage, raindrops, and other objects are not hazardous targets [F2].

**Water Reflections** - Specular reflections from standing water do not present a significant additional hazard to personnel outside of the NHZ [F2].

**Retro Return** - The retro return will be less than 0.5% of the radiant intensity from the output laser beam. This exposure does not constitute a safety hazard.

**Extended Source** - The extended source limitation is not valid since the beam will not produce diffuse reflections that will constitute an eye hazard.

**Standard Operating Procedure** - See the attached procedure 2 (Section F5).

#### **F2.8 Case H: Targeting Beam with Doubled Nd:YAG Laser for Clay Target (1 m Diameter Beam at 62 m Distance)**

**Radiant Exposure** -  $2.7 \times 10^{-5} \text{ J/cm}^2$

**MPE** - See the values listed in Section F1 for the Nd:YAG laser MPEs. Comparing the MPEs to the radiant exposure in this experiment yields the following:

**Ocular:**  $\text{OD}_{\text{safe}} = 2$ . In near-field viewing, the same safety procedures should be applied as at the laser source. Standard Glendale Nd:YAG safety glasses will be used.

In the far-field, such as in or over water, no transient personnel are expected. All traffic must be excluded from the NHZ detailed below. Any control personnel in the area should wear the eye protection specified above.

**Skin:** 2 orders of magnitude below the exposure threshold for 10 s exposure.

NHZ - See Figs. F1(b) and F8. Barriers will be placed to deny access to the hazard zones behind CBD, Building 250. Red lights will be in operation outside the building and danger signs in place when the laser is firing. Test control and the NRL boat will control traffic in the NHZ as required. All safety procedures cited in A (SOP 1) will be used in Building 250. All range control procedures described in SOP 2 will be used.

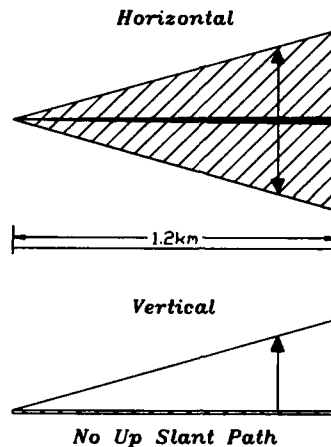


Fig. F8 — NHZ for Case H

NOHD - The NOHD is 1.2 km assuming a worst case of no atmospheric attenuation. For this lens,  $\phi$  is  $7.5 \times 10^{-3}$  rad.

Diffuse Reflections - The maximum radiant exposure that will produce hazardous reflections from an Nd:YAG laser is  $20 \text{ J/cm}^2$  for an exposure of 0.25 s [F1, Table 3]. Reflections from the fence or the water tower will not produce reflections that are hazardous outside of the NHZ. Glossy foliage, raindrops, and other objects are not hazardous targets [F2].

Water Reflections - Specular reflections from standing water do not present a significant additional hazard to personnel outside of the NHZ [F2].

Retro Return - The retro return will be less than 0.5% of the radiant intensity from the output laser beam. This exposure does not constitute a safety hazard.

Extended Source - The extended source limitation is not valid since the beam will not produce diffuse reflections that will constitute an eye hazard.

standard Operating Procedure - See the attached procedure 2 (Section F5).

### F3. LENS CALCULATIONS

For a 2.5 cm collimated beam at the laser scanner, any 1:3 lens will suffice. A negative (concave) lens must be the first lens in the collimating telescope to eliminate atmospheric breakdown.



However, this telescope arrangement severely reduces the divergence  $\phi$  of the laser beam to 0.2 mrad and leads to divergences that are inadequate to achieve the required beam diameters at the desired experimental distances. For example, the divergence from the above telescope yields the following beam radii  $r$  at the indicated distance  $d$  where  $r = d\phi$ .

$d(\text{m})$	$r_{div}(\text{cm})$	$r_{req}(\text{cm})$
15	0.6	5
30	1.22	15
1500	61	1500
3000	122	1500

A large collimating telescope cannot be used because of the limiting clear aperture (2.5 cm) of the scanner. Therefore, a diverging lens must be employed.

Simplistically shown in Fig. F9, the focal length is given by

$$fl = 3(\text{mm}) \cdot \frac{d}{r} \quad (\text{F17})$$

In summary, the following lenses must be used.

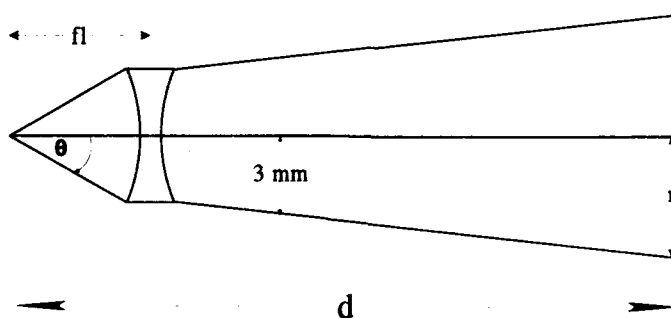


Fig. F9 — Description of the focal length calculation

### F3.1 Case A: 1.25 cm Doubled Nd:YAG Laser Beam on the Target Board at 15 m Distance

This is attained by diverging the laser beam with no lens in place.

### F3.2 Case B: 1.25 m Doubled Nd:YAG Laser Beam on Target Board at 16 m Distance (1.75 m Diameter)

Focal length = -5 cm.

### F3.3 Case C: Doubled Nd:YAG Laser Beam on Targets Along Light Tunnel (20 cm at 61 m, 5 cm at 15 m)

All targets/distances are designed with the same IFOV so that one lens will be used. Focal length = -180 cm.

**NOTE 1:** This is a very long focal length lens that is not available. Using a shorter focal length lens will provide a larger beam. If the power of the laser allows for the larger beam, this is recommended.

**NOTE 2:** Longer focal length lenses are possible if positive lenses are used. If a long positive lens can be used without causing atmospheric breakdown at the focal length, this is an alternate solution.

**NOTE 3:** The largest commonly available lens is -100 cm. A -100 cm lens will yield a beam that is 3.6 in. in diameter at 50 ft.

#### **F3.4 Case D: Targeting Beam with Argon Ion Laser for Slug**

15 cm beam at 31 m distance: focal length = -120 cm.

30 cm beam at 31 m distance: focal length = -60 cm.

See Notes 1, 2, and 3 above in Case C.

#### **F3.5 Case E: Targeting Beam with Doubled Nd:YAG Laser for Slug**

15 cm beam at 31 m distance: focal length = -120 cm.

30 cm beam at 31 m distance: focal length = -60 cm.

See Notes 1, 2, and 3 above in Case C.

#### **F3.6 Case F: Targeting Beam with Doubled Nd:YAG Laser to Boat**

15 cm beam at 1.5 km distance: focal length = -60 cm.

15 cm beam at 3 km distance: focal length = -120 cm.

See Notes 1, 2, and 3 above in Case C.

#### **F3.7 Case G: Targeting Beam with Argon Ion Laser for Clay Target**

1 m beam at 62 m distance: focal length = -40 cm.

#### **F3.8 Case H: Targeting Beam with Doubled Nd:YAG Laser for Clay Target**

1 m beam at 62 m distance: focal length = -40 cm.

### **F4. HEALTH AND SAFETY PROCEDURE 1 (CBD, BUILDING 250)**

- 1. DANGER - VISIBLE AND INVISIBLE LASER RADIATION - AVOID EYE OR SKIN EXPOSURE TO DIRECT OR SCATTERED RADIATION.**
2. Inexperienced personnel must be accompanied in the laser area by a qualified laser operator.
3. Workers are not to view the beam directly.
4. Ensure that the laser warning lights are on in the laser area and that all doors are locked.
5. Determine that all laser warning signs are in place.

6. Protective eyewear (spectacles or goggles) must be worn by all personnel in the laser area while any laser is operating.
7. Eye protection must be worn when using an alignment laser.
8. Eye protection must be worn when viewing reflections off of laser locating cards.
9. Avoid direct exposure of the skin with the laser radiation.
10. Ensure that beam stops or partitions are in place along the laser path before starting the laser.
11. Know where shock hazards are located. Lasers and power supplies are serious shock hazards.
12. Ensure that safety railings are in place when the laser is not in use.

#### **F5. HEALTH AND SAFETY PROCEDURE 2 (CBD, BUILDING 250)**

1. **DANGER - VISIBLE AND INVISIBLE LASER RADIATION - AVOID EYE OR SKIN EXPOSURE TO DIRECT OR SCATTERED RADIATION.**
2. Inexperienced personnel must be accompanied in the laser area by a qualified laser operator.
3. Workers are not to view the beam directly.
4. Ensure that the laser warning lights are on in the laser area and that all doors are locked.
5. Install outdoor barriers to deny access to outdoor firing area.
6. Determine that all laser warning signs are in place on outdoor barriers.
7. Protective eyewear must be worn by all personnel in the laser area while any laser is operating.
8. Avoid direct exposure of the skin with the laser radiation.
9. Know where shock hazards are located. Laser power supplies are serious shock hazards.
10. Ensure that safety railings are in place along the laser path when the laser is not in use.
11. Ensure that beam stops or partitions are in place along the laser path before starting the laser.
12. Verify that the area is free of specular objects before starting the laser. Covers or lusterless paint should be applied to objects that cannot be removed.
13. In the absence of specular surfaces, range control is limited to the direct beam path of the laser.
14. Determine buffer zones and nominal hazard zones for the test in progress (figures supplied).
15. Notify Test Control prior to start of the outdoor test. Institute test control procedures. Verify the area is free of traffic.

16. Enter laser firing in the log of outdoor laser firings.
17. Enter slug or clay target shots in log of live firings.
18. No laser operation may involve an upward slant path.
19. Radio communication with downrange personnel shall be provided to verify eye protection is worn.
20. Range flags will be used to indicate laser and live firings are in progress.
21. The laser must be blocked when not in use to avoid accidental discharge.

**EMERGENCY SHUTDOWN PROCEDURE - TURN KEY IN LASER POWER SUPPLY TO OFF**

**REFERENCES**

- F1. American National Standard for the Safe Use of Lasers, ANSI Z136.1-1986. American National Standards Institute, New York, New York (1986).
- F2. Occupational and Environmental Health: Control of Hazards to Health from Laser Radiation, TB MED 524. Department of the Army, Headquarters, June 1985.

## **Appendix G**

### **TURN-ON PROCEDURES FOR THE DIGICON EXPERIMENT**

#### **I. NRL Laser Radar Receiver Turn-On Sequence:**

- 1) Put on safety glasses.
- 2) Turn on Master Switch, located above the monitor on the 19 in. rack.
- 3) Turn on computer and answer "y" to the prompts as follows:
  - a. Initialize Point I (takes 3 minutes).
  - b. Initialize Burr-Brown.

**NOTE:** For reboot, initialize Burr-Brown, not Point I.

- 4) Turn on Preamp Power Supply, which is a rocker switch located on the lower left of the 19 in. rack.
- 5) Turn on Focus Current Power Supply, which is the rocker switch below the Preamp Power switch.
- 6) Turn on Deflection Power Supply, which is the rocker switch located on the lower right of the 19 in. rack.
- 7) Turn on CAMAC Crate located above the monitor screen (switch is on the lower left side of crate).
- 8) Turn on NIM-BIN(2) with 612AM amplifiers located in 19 in. rack.
- 9) Turn on NIM-BIN(1) with FTA820 amplifiers located underneath RF shielded receiver box.
- 10) Turn on Tennelec Diode bias to 40 V as follows:
  - a. Pull out switch "a" and move up (voltage on).
  - b. Pull out switch "b" and move up (current limit).
  - c. Turn voltage knob clockwise four and one half (4.5) turns, checking the LED display, to 40V. **NOTE:** Toggle switch should be in V position.
  - d. After setting to 40 V, change switch "b" downward (current limit to 1  $\mu$ A).
- 11) Turn on ANTEL Optronics Photodetector Supply to -80 V as follows:
  - a. Turn left switch to volts position.
  - b. Adjust right knob clockwise, checking the LED display, to -80 V.
  - c. Turn left switch to  $\mu$ A position.

**NOTE:** Upon shut down, turn down voltage dial before turning off.

- 12) Turn on High Voltage Switch on High Voltage box and power strip.
- 13) Turn on High Voltage Enable switch located on bottom right of 19 in. rack.
- 14) Follow the Receiver Software Manual to run the program.

**NOTE:** Turn-off sequence is the reverse order of the above steps.

#### **II. Laser Turn-On Sequence:**

- 1) Turn water on.
- 2) Turn on breaker in back of the power supply.
- 3) Turn key on in front of the power supply (Green light on the LU660 should be on. If green light is off, check Securities in the laser manual,\* pp. 2-9 (includes water level, temperature, flow, etc.)).

---

\*Operation and Maintenance Manual, Quantel International YG660 & 661 YAG laser, QIOM 145, March 1989, Rev. a.

- 4) After 8 seconds, the red light on the CB631 comes on.
- 5) Push FIXED on the LU660 (Q-switch off) to get the flashlamp going. (The voltage level should remain at 1.3 kV for 200 mJ output at 532 nm.)
- 6) Wait 20 minutes.

III. Laser Turn-Off Sequence:

- 1) Close the beam dump (and external shutter).
- 2) Turn the Q-switch off.
- 3) Close the shutter.
- 4) Go to MANUAL.
- 5) Hit FIRE to take the charge off the capacitor (lights go out).
- 6) Turn key off.
- 7) Turn breaker off.
- 8) Turn water off.

IV. Digicon Control Of Laser Turn-On Sequence:

- 1) Turn on Triple O/P DC power supply and ramp up right side to 30 V, leave left side as set (should be set to 5 V).
- 2) After *lr* program has been started on the IBM AT, do the following:
  - a. Hit External on the LU660 (Q-switch off).
  - b. Switch SB660 from Normal to External.
  - c. Hit shutter "ON" button on LU660.
  - d. Raise manual shutter.

NOTE: Now charging, firing, and Q-switching are controlled by the IBM AT.

## Appendix H

### SUMMARY OF COMMANDS TO RUN THE DIGICON LASER RADAR DEMONSTRATION

The Science Applications International Corporation Laser Radar Receiver Documentation CDRL A007 (8/7/90) includes all of the commands to run the Digicon laser radar. Presented here are some basic commands used to run demonstrations of the system looking at seven targets down a 60 m light tunnel. The program that controls the receiver is entitled *lr*.

#### 1) Demonstration of the 3-D Display

<i>lr</i>	
<i>hi on</i>	(turn on high voltage)
<i>set flag disp both</i>	(both IBM and Clipper displays on)
<i>set flag nrl_1 30</i>	(run at 1 Hz)
<i>set scanner point 33200 32800</i>	(point the laser)
<i>set flag disp 3d</i>	(3-D display)
<i>clip gray</i>	(gray scale images)
<i>set def 1 -0.02 -0.12</i>	(point the Digicon FOV)
<i>t</i>	(run the test; observe a rotating target)
Hit return to stop the test.	

#### 2) Demonstration of the Deflection Display

<i>set targ 2</i>	(2 targets)
<i>set flag disp clip</i>	(Clipper display only)
<i>set flag disp def r</i>	(range images on deflection screen)
<i>clip color</i>	(pseudo-color scale)
<i>set mag 3</i>	(show FOV's actual size relative to FOR)
<i>set flag nrl_1 15</i>	(run at 2 Hz)
<i>t</i>	(run test; note size of FOVs; also note # of frames/time = frequency)
Hit return.	
<i>set mag 8</i>	
<i>set targ 7</i>	
<i>clip gray</i>	
<i>set flag disp def i</i>	(intensity images on deflection screen)
<i>set int thresh 400</i>	(set intensity threshold)
<i>t</i>	(run test to observe magnified intensity images of seven targets)
Hit return.	

## 3) Take data at 10 Hz and play back.

To save the data:

```
set flag nodisp both      (turn off both displays)
set flag coor dis         (disable coordinate transformation)
set flag nrl_1 3          (run at 10 Hz)
set fl cal dis            (disable calibration procedure)
ext save
t
```

Hit return after approximately 100 frames.

To play back:

```
clip color
set flag cal ibm
set flag coor ibm
set flag disp clip
set flag disp def r
ext read disp 100        (observe playback of 100 frames of range images
                           on the Clipper display).
```

4) Simulate a  $24 \times 24$  pixel Digicon:

Use bb\_def02.def, laser02.def, and delay02.dat in lr.ini file. These are the data files that list Digicon deflection coordinates, laser scanner coordinates, and delays for the amplitude gate; currently they are included in the lr2.ini file. Thus, to simulate a  $24 \times 24$  diode array, reinitialize with lr2.ini in place of lr.ini:

```
hi off
dos
copy lr.ini lr1.ini
copy lr2.ini lr.ini
exit
init
hi on
set targ 9
set flag disp clip
set flag nrl_1 15
t
```